ENVIRONMENTAL MONITORING OF EFFLUENT PLUMES IN COASTAL NEWFOUNDLAND

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by

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ABSTRACT

It is important to first understand the components and fate of an effluent plume in the receiving environment before its effects can be fully understood. The purpose of this work was to identify sensing technologies that can be used to monitor an effluent plume in the coastal environment and use selected sensors to compare the observed results with a predictive model.

The three major coastal wastewater streams in Newfoundland and Labrador are seafood processing effluent, municipal wastewater and produced water. Each has various properties and components that should be considered when studying the plumes' potential effects. Once an outfall is established in a coastal environment, it is essential to continue monitoring to determine if there are any effects to the receiving environment. Both traditional and *in situ* sampling can be utilized in this task. Traditional sampling involves the use of bottles or divers to obtain samples at predefined coordinates. *In situ* sampling refers to the use of continuous sensors on a platform such as an autonomous underwater vehicle (AUV) to obtain measurements instantaneously (or the duration of sensor processing time) without the removal of the specimen or sample. *In situ* sensors are capable of measuring physical, chemical or biological parameters.

Seafood processing waste represents the largest source of organic wastes in the province of Newfoundland and Labrador, yet is the least understood. Therefore, it was selected for further study. Trials were conducted at a seafood processing plant in Aquaforte, NL in October, 2004. Measurements were taken with a fluorometer (calibrated to detect

rhodamine WT), a CTD sensor (used to measure conductivity, temperature and depth) and a dissolved oxygen sensor mounted on the back of an 18 ft inflatable boat equipped with an electric trolling motor to limit plume disturbance. Continuous spatial data corresponding to sensor information was obtained using a global positioning system (GPS) unit. Spatial and oceanographic data were integrated to obtain a visual and quantitative representation of the plume.

Temperatures in Aquaforte Harbour were relatively constant with variations within one degree Celsius. Salinity was correlated with temperature and was shown to decrease towards the outer harbour region. Dissolved oxygen values were found to be supersaturated for all trials. Rhodamine WT (RWT) was found to follow a typical plume trend and was used for further plume analysis.

A comparison of the RWT plume was conducted with the plume dispersion model, CORMIX. It was determined that this type of model can be used to simulate seafood processing wastes given that all the variables in the model are known. The trials were successful in demonstrating the use of this sensor package and dispersion model for monitoring a seafood processing effluent plume.

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TSS	total suspended solids
BOD	biological oxygen demand
COD	chemical oxygen demand
TOC	total organic carbon
FOG	fats, oil and grease
PCB	polychloride biphenyl
PAH	polycyclic aromatic hydrocarbon
DO	dissolved oxygen
DO_s	dissolved oxygen saturation point
TS	total solids
TDS	total dissolved solids
AUV	autonomous underwater vehicle
CNLOPB	Canada - Newfoundland and Labrador Offshore Petroleum Board
CORMIX	Cornell Mixing Zone Expert System
C-SCOUT	Canadian Self-Contained Off-the-shelf Underwater Testbed
PSU	practical salinity unit
ATP	adenosine triphosphate
DMS	dimethyl sulphide
ORP	oxygen reduction potential
A	absorbance
C	analyte concentration
ε	coefficient of molar absorption
L	length of the flow cell
RWT	rhodamine WT
CTD	conductivity, temperature and depth
DOM	dissolved organic matter
DOC	dissolved organic carbon
GPS	global positioning system
ppb	parts per billion by volume
USB	universal serial bus
PVC	polyvinyl chloride
SE	standard error
VOC	volatile organic compound
IDW	inverse distance weight
u_a	ambient current velocity
C_{obs}	observed concentration of rhodamine WT
C_{pred_i}	predicted concentration
d	centerline distance of plume
R^2	Nash-Sutcliffe coefficient

Chapter 1 Introduction & Background

1.1 Introduction

Effluent originating from human activities on land has greatly contributed to the pollution and degradation of the world's oceans and coastlines. Sources include both point and non-point sources such as pulp and paper mills, fish plants, and sewage outfalls of the former and agriculture and municipal run-off of the latter. It is estimated that 70% of the world's population will live within 100 km of the ocean in the next 20 years (Pinet, 2000). Therefore, it is necessary to maintain ocean water quality acceptable not only for human health but also for the quality of receiving coastal environments.

In the province of Newfoundland and Labrador, the major sources of land-based pollution by volume are from seafood plant processing and municipal wastewater. Produced water from the offshore oil and gas industry also contributes to the liquid wastewater in the province, but is released approximately 300 km east of Newfoundland therefore does not pose a great threat to coastal ecosystems. It is estimated that seafood-processing plants contribute the highest organic load to the coastal environment (Cull, 2000). In some cases, plants operate and dispose of waste in low energy bays, coves or inlets that do not promote adequate flushing to remove, disperse and dilute the waste. Within the scientific literature to date there has been limited research on the effects of this waste on the receiving environment in Newfoundland and Labrador (L. Park, pers. comm.).

This work reviews typical types of effluent plumes in Newfoundland and Labrador and their characteristics. Further, a review of some major indicators used by the

oceanographic community is completed to ensure that it is possible to effectively assess the potential impact to the environment of the effluent. It also examines the use of an autonomous underwater vehicle (AUV) as a sensor platform instead of traditional sampling technologies. An experiment is completed using a selection of sensors to trace and map a simulated seafood effluent plume to determine the extent of the near-field zone in comparison with a dispersion model.

1.2 Effluent Plumes

Humans have used the oceans as a dumping ground for a vast array of substances for hundreds of years. The coastal zone receives the majority of this waste. It is estimated that eighty percent of all global marine pollution originates from land-based sources (AMEC, 2003). Effects on the receiving environment can vary depending on the fate and composition of the waste. It is important to control the amount and type of waste products being deposited along the coastal environment to promote the economic viability of the fishery, aquaculture and tourism industries.

On the island portion of the province of Newfoundland and Labrador, the two major contributors of organic waste are seafood plant effluent and sewage (Cull, 2000). A summary of the approximate inputs from 1992-1996 is shown for Newfoundland in Table 1.1. It is estimated that fish offal is the largest source of organic waste to the coastal environment.

Table 1.1 Organic waste inputs for coastal Newfoundland from 1992-1996 (Cull, 2000)

Year	Offal (kg)	Sewage (kg)	Sawmills (kg)	Aquaculture (kg)
1992	159,000,000	5,320,000	3,204,000	49,100
1993	90,500,000	5,640,000	3,659,000	127,000
1994	86,000,000	5,970,000	3,580,000	231,000
1995	112,000,000	6,290,000	4,225,000	340,000
1996	131,000,000	6,620,000	4,446,000	607,000
Total	578,500,000	29,840,000	19,114,000	1,354,100
Avg.	115,700,000	5,968,000	3,822,800	270,820

1.2.1 Seafood Processing Plants

Background

The fishing industry has always been a major economic force for the province of Newfoundland and Labrador. In 2004, 117 licensed primary processing plants employed over 14,000 individuals from approximately 500 different communities (Figure 1.1) (DFA, 2005). In the past, the industry was the largest employer and maintained rural coastal communities. However, the fishery has significantly decreased over the past years due to the Atlantic cod (*Gadus morhua*) moratorium in the early 1990s (Schrank, 2004). Further, the number and variety of primary and secondary processors has changed as the fishery has changed due to alteration in the fish stocks, DFO regulations and quotas, market demands, political, economic and environmental factors (Ming-Lesage, 1991). The fishery has shifted from an emphasis on groundfish to shellfish as a result of the above factors (Schrank, 2004). Table 1.2 represents the value and volume of Newfoundland and Labrador seafood landings before and after the moratorium and demonstrates this shift in the Newfoundland and Labrador economy. There are fewer metric tons (mt) of seafood landed in the province yet the value of the catch has greatly

increased. Note in Table 1.3 that the number of processor licenses has also decreased as the market demand and availability of raw products has changed. The fishery still represents a major economic sector in the province; hence, careful consideration should be given to the implications of its waste management practices. Characterization of the processing wastewater is particularly important not only for the protection of the ecosystem but also for the sustainability of the fishery itself (Islam et al., 2004).

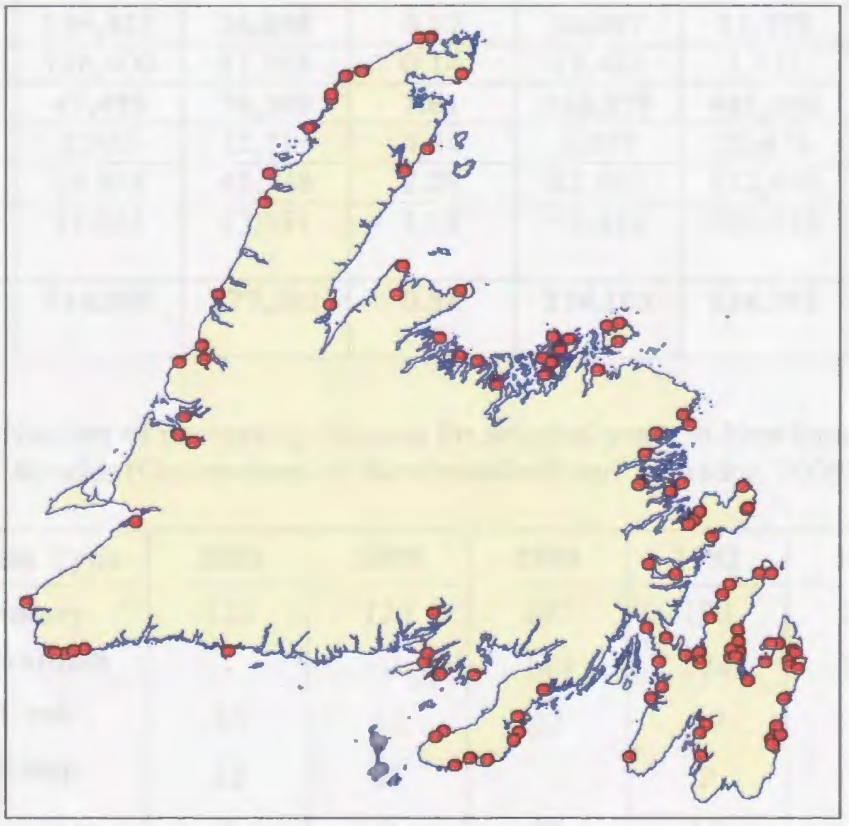

Figure 1.1 Fish plant locations for the island portion of Newfoundland
Note: Used with permission from Laura Park, Fisheries and Oceans Canada

Table 1.2 Newfoundland and Labrador seafood landings (Schrank, 2004)

Species	1990			2002		
	Quantity live weight (mt)	Value ('000) $Cdn	Value/ quantity	Quantity live weight (mt)	Value ('000) $Cdn	Value/ quantity
All groundfish	**336,588**	**174,018**	**0.52**	**60,127**	**62,297**	**1.04**
Cod	245,896	133,698	0.54	21,076	27,191	1.29
Flatfishes	41,451	16,713	0.40	14,223	11,416	0.80
Greenland halibut	16,986	13,537	0.80	9,656	10,627	1.10
All finfish	**159,923**	**26,855**	**0.17**	**50,097**	**13,378**	**0.27**
Capelin	126,600	17,165	0.14	13,482	1,732	0.13
All shellfish	**47,495**	**76,369**	**1.61**	**163,879**	**441,106**	**2.69**
Lobster	2,926	12,713	4.34	2,057	23,476	11.41
Shrimp	19,998	45,748	2.29	82,862	172,446	2.08
Queen/snow crab	11,054	13,051	1.18	59,422	229,253	3.86
Total fish & shellfish	**544,006**	**277,242**	**0.51**	**274,103**	**516,781**	**1.89**

Table 1.3 Number of processing licenses for selected years in Newfoundland and Labrador (Government of Newfoundland and Labrador, 2005)

License Type	2002	2000	1996	1992	1988
Primary	123	125	197	193	214
Groundfish	-	-	144	174	177
Crab	36	32	22	19	18
Shrimp	12	11	-	2	11
Secondary	7	9	25	11	-
Aquaculture	5	5	6	-	-

Waste from the seafood processing industry can vary significantly as determined by the end-products and waste management practices of the plant. Inputs into a processing plant can include whole fresh or iced seafood, water, ice, calcium hypochlorite and other

chemicals (217 approved by government), packaging materials, and electricity (AMEC, 2003). These inputs are directly related to the processor's facility size and targeted species. Outputs may include fresh chilled fillet exported or consumed; swim bladders; skins of fishes (like sharks and rays); remaining fats, carcasses (with swim bladders removed) and fillets rejected for quality control used to make fish meal or silage; wastewater of varying strengths, especially from filleting and trimming processes which contain fats, oil and grease (FOG) with blood, small pieces of fish and protein; waste heat from ice manufacture, chilling and the cold room (AMEC, 2003).

Recovering waste products to a secondary market for fishery by-products can be useful in reducing the amount of waste deriving from processing operations. There are areas in the world such as Alaska and Iceland where waste diversion is a critical part of the processing strategy (Bluhm and Becthel, 2002; Islam et al., 2004). There are currently five processors of by-products in Newfoundland and Labrador including two fishmeal plants, one shell drying facility, one seal oil facility and one silage plant (T. Thomas, pers. comm., 2005). There is a disproportionate ratio between the primary and secondary processors. Considering the availability of materials, there is potential for resource development that is currently under-utilized within the province.

Environmental Effects

Seafood processing wastes, fish parts, culls and inedible species have been discarded into the sea or at sea since the time that humans began to fish (Champ et al., 1981). Some of the problems associated with disposing of fish plant effluent directly into the coastal environment can include but are not limited to: a turbidity plume; accumulation of heavy

metals from fish flesh and shells at poorly flushed dump sites; anoxic benthic environments with poor circulation leading to decrease in life; a reduction of aesthetic quality including floating solids, surface oil slicks, odour, and flies; an increase in scavengers and exotic species; and an increase in nutrients leading to eutrophication (Champ et al., 1981; Barrie, 1985). There is also the potential for bacterial contamination in the form of *E. coli* and Salmonella if the receiving environment is adjacent to surrounding shellfish areas and aquaculture sites such as along the south coast of Newfoundland (Menon and MacDonald, 1978; Tidmarsh et al., 1986; Coastal Zone Research, 2004).

Little information exists on waste characterization and quantification of fish plant effluents in Atlantic Canada (Broderson, 1972; Tidmarsh et al., 1986; S. Fudge and Associates, 1989; Cull, 2000; AMEC, 2003). Exact figures are not available because each fish plant has a range of production capabilities, use different production methods and treat their waste differently. Most fish plants are privately owned and operated commercial enterprises; it is not advantageous for them to share production information, hence the lack of published data.

Waste quantity and components can vary considerably depending on the species, stage of processing and processing methods. The proportion of waste material can range from 30 to 60 percent of the catch for groundfish to up to 80 percent for shellfish (AMEC, 2003; Islam et al., 2004). It is estimated that 51% of the landed weight is waste in Atlantic Canada (AMEC, 2003).

There are both liquid and solid wastes that are generated by most seafood processing operations. The spatial and temporal scale of the impacts will vary due to the amount and nature of the waste output (Islam et al., 2004). The raw waste contains varying amounts of solid matter including offal (internal organs), skin, bone and shells depending on the species (AMEC, 2003). A large amount of potable water is required for the various steps in the processing (Coastal Zone Research, 2004). The production of seafood products requires mechanical action as well as water to act vigorously on the raw product which forms effluent containing particles of a wide range of sizes. These particles are largely organic matter including proteins and their derivatives: FOG (Coastal Zone Research, 2004). The term used to refer to the particulate matter in the effluent is total suspended solids (TSS).

Liquid effluent will generally have high biochemical oxygen demand (BOD), oil and grease, and nitrogen content. BOD refers to the amount of oxygen that is biologically required to degrade the organics in the wastewater. Chemical oxygen demand (COD) refers to the oxygen required to chemically oxidize the organic wastes in water. COD is generally higher than BOD because more compounds can be chemically oxidized than biologically oxidized by bacteria. Both parameters are used in the measurement of total organic carbon (TOC). They are also often used to measure the organic matter in industrial and municipal wastes that contain compounds that are toxic to bacteria (Pinet, 2000).

AMEC (2003) made the several observations about the discharge profiles from recent and historical data. BOD (mg/L) value ranged from 10 to 110,000 while COD (mg/L) ranged

from 496 to 140,000 and the TSS (mg/L) had a range of 0.26 to 125,000. The contaminant load was dependant on the type of seafood product being processed. In general, groundfish process water had the lowest contaminant discharge while fishmeal processing was higher than either shellfish or finfish. Lower BOD and nitrogen can be expected from shellfish processing compared to flesh fish. By process/species, fresh salmon had the lowest contaminant load while marinated herring had the highest. Table 1.4 represents a summary of production based contaminant discharge for several species.

Table 1.3 Production based contaminant discharges (Islam et al., 2004)

Species	Water Flow (m^3day^{-1})	BOD (mgL^{-1})	COD (mgL^{-1})	TSS (mgL^{-1})	FOG (mgL^{-1})
Shrimp	400-1,100	720-2,000	1,200-3,300	800-900	250-700
Crab	3000	4,400	6,300	620	220
Clams	1,300-13,500	500-2,500	1,000-4,000	600-6,000	20-50
Scallops	50-500	200-1,000	300-1,100	1,000-4,000	15-25
Herring	150	1,200-6,000	3,000-10,000	600-5,000	600-800
Tuna	125-300	700	1,600	500	250
Salmon	250-2,500	250-2,600	300-5,500	120-1,400	20-550

Beyond the physical properties in the liquid effluent, there can be a wide range of other chemical and biological contaminants of concern. Nitrogen in the form of ammonia is present in the blood and slime of many fish and shellfish species (AMEC, 2003). It is also used as a disinfecting agent along with chlorine and other process aides, disinfectants and cleaners which can be acutely toxic to fish.

Dockside waste such as litter and petroleum leakage can be disposed of through the plant outfall as part of typical unloading operations which can result in an accumulation of toxic chemicals. Heavy metals and polychlorinated biphenyls (PCBs) can be found in the fish waste at outfalls. Such chemicals accumulate in the fish through bioaccumulation. Small amounts have been found in Atlantic Canada coastal regions from human sources (Broderson, 1972). In fact, small amounts of PCBs can be found everywhere in the ocean as they have been found to stream across the globe on air currents from unregulated burning (Pinet, 2000). In 1978, a study was conducted to determine if there is any relationship between levels of PCBs in sediments and fish processing outfalls. At six of the ten sites studied there appeared to be an association with levels reaching an average of 25 ppb (Wiltshire, 1978). It was noted however, that significant accumulations of PCBs are likely to occur only where the discharge strength of effluents was high and/or the poor dispersal of effluents led to highly enriched sediments of fish wastes. In other words, high levels of PCBs may occur where there are large of amounts of effluent discharging into a poorly flushed receiving environment. Other types of hazards that can be present in the surrounding vicinity of fish plants and their outfalls include fecal coliform and other bacteria from seabirds (AMEC, 2003).

If there are any metals or accumulated chemicals in the viscera or shells, there is potential for leaching into the sediment of the surrounding environment at the gurry ground or disposal site. These metals can be a result of discharges from industrialized and urbanized areas (Pinet, 2000). The trace amounts of metals enter the food chain through its absorption in plankton. The poisonous substances build up in the tissues of marine

organisms along the food chain to species that humans consume. It was found at a finfish gurry ground that there were elevated levels of metals in some sediment and benthic organisms (Barrie, 1985; S. Fudge and Associates, 1989). These results may not be relevant to the current industry in Newfoundland and Labrador due to larger proportion of shellfish being processed compared to finfish 15 to 20 years ago. Shells from crab and other scavenger species are less likely to decompose (Cull, 2000) and will sink directly to the bottom resulting in large areas of decomposing seafood waste (Bluhm and Becthel, 2002).

If the receiving environment cannot assimilate the waste products efficiently, the water quality of the area will diminish rapidly. Two studies (Barrie, 1985 and S. Fudge and Associates, 1989) used underwater photography to show that several dump sites in Newfoundland contained large amounts of black ooze with white sulphur-oxidizing bacteria encrusted on the outer surface indicating low oxygen levels associated with dumpsites. Further, they observed through SCUBA surveys that there was a void of life in the immediate vicinity of the disposal site both vertically and horizontally, with a very limited presence of macrofauna or scavengers.

However, this phenomenon was not present in the water column surrounding the outfall. Champ et al. (1981) observed through a SCUBA study that some fish species were commonly associated with processing plants outfalls in coastal waters. These included several scavenger species such as flatfish, cunners, tom cods, sculpins and wolf fish. Also, large schools of herring or mackerel were observed to have feeding forays into the effluent during times of high production (Broderson, 1972; Champ et al., 1981). There

was no indication of the sea floor conditions adjacent to the outfall but it is assumed that if decaying matter settles below the outfall, anoxic conditions will result. Broderson (1972) characterized waste by estimating the BOD, COD, TSS, oil content and total volatile solids. The study concluded that fish plant effluents tend to be site and species specific but in general BOD, TSS and oil were high as expected.

Waste management procedures of the fish processing industry in Newfoundland and Labrador are not regulated or monitored on a regular basis (Park, pers. comm.; Thomas, pers. comm). As a result, there are many examples across the province where liquid waste is pumped into the ocean without screens or treatment. A common practice in solid waste disposal involves the use of a barge below the outfall to collect the solids before being towed out to a gurry ground (Tidmarsh et al., 1986). One such example in Figure 1.2 shows shrimp shells being collected in a barge prior to being towed offshore.

Figure 1.2 Solid waste collection at a shrimp processing plant

The ideal practice would involve a series of screens and treatment processes as seen in Figure 1.3. Typically screens are used to gather most settable solids, collected for disposal or reprocessing into by-product materials such as fishmeal. The remaining suspended and dissolved solids are discharged as effluent along with the wastewater. In order to reduce wastes during fish processing operations one can conserve water, improve housekeeping methods, control of raw material quality and adopt technological modifications as they improve (Islam et al., 2004). The organic matter should break down quickly once it reaches the marine environment. There is a wide range of available treatment technologies once the waste has been discharged as identified in Jamieson and Gagnon (2005) which is beyond the scope of this work.

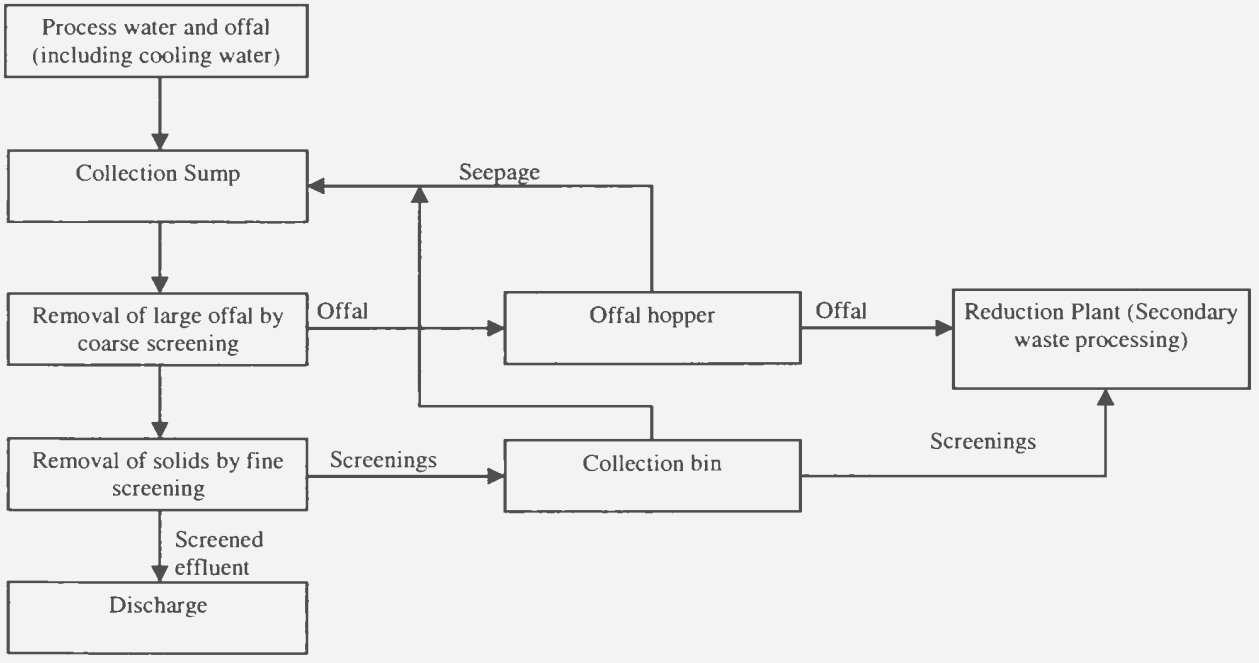

Figure 1.3 Typical fish plant processing waste management practices (AMEC, 2003)

Regulatory Review

The regulations for monitoring and maintenance of fish waste disposal sites (or gurry grounds) are not well enforced in Newfoundland and Labrador (Cull, 2000). Since there is a lack of monitoring or regulatory data reporting, there is little incentive to comply with guidelines. This does not imply, however, that all plants do or do not comply with regulations.

There are currently no Environment Canada regulations that are specifically related to the discharge of effluents from seafood processing plants (Coastal Zone Research, 2004). There are two national laws related to pollution prevention: the *Canadian Environmental Protection Act* (1999) and certain provisions of the *Fisheries Act* (1985). However, there is a set of guidelines outlined by the Canadian government entitled *Fish Processing Operations Liquid Effluent Guidelines* (1975) but there are no incentives to follow these guidelines and there are no governmental agencies that monitor this waste stream on a regular basis (L. Park, pers comm.). The guidelines indicate that there should be a screen present to filter all solids, the outfall should discharge below low tide level, certain high strength wastes associated with fish meal processing should be recovered and there should be general good housekeeping (Tidmarsh et al., 1986).

The practice of dumping fish offal at sea is expressly prohibited through the *1996 Protocol to the London Convention* (1972) except when a permit is issued by the proper authoritative body. Under the Ocean Dumping Control Act, a permit can be obtained for the disposal of wastes of more than 450,000 kg/yr issued by environmental protection officers (Tidmarsh et al., 1986). The practice is approved for processors in

Newfoundland and Labrador who cannot feasibly transport their solid wastes to an approved waste disposal facility or fishmeal plant for recycling. At the present time, Newfoundland and Labrador is the only province in Canada in which exemptions from the provisions of the *London Convention* are permitted under the *Canadian Environmental Protection Act* ocean dumping provisions. In 2003, 48 permits were issued to Newfoundland and Labrador processors (AMEC, 2003). Site-specific data was not available but it was noted that the sites were selected with a preference for rocky bottoms with high-energy sea conditions (AMEC, 2003). It was reported that the offal was not dispersed or degraded as predicted at several test sites. There are reports that in some instances the fish waste is not brought to the permitted site but released either along the way or right from the wharf (Cull, 2000).

An action plan was initiated through the National Program of Action for the Protection of the Marine Environment from Land-based Activities. The program represents a collaboration of government departments and agencies to understand and eliminate coastal pollution. A working group has formed to investigate the current state and potential effects of the seafood processing industry in Atlantic Canada. This group has recently formed, the initial analysis of the regions nearly 800 plants has been done and further work will be completed in upcoming years (L. Park, pers. comm.).

1.2.2 Municipal Wastewater

Background

Another serious hazard to the coastal ecosystem is the large input of municipal wastewater discharged into coastal water throughout the province. It can include both

the liquid waste from a community's sewer system as well as from municipal treatment facilities (EC, 2001). The waste stream can be separated into two broad categories: sanitary sewage and storm water. Sanitary sewage includes the liquid waste from homes, businesses, institutions and industries while storm water derives from rain or melting snow from rooftops, lawns, roads, and other urban surfaces. According to estimates made in 1999, municipal wastewater discharges represented one of the largest single effluent discharges by volume in Canada with 14.4 million m^3 per day of treated wastewater being discharged from 1118 municipalities (EC, 2001).

Numerous studies have been conducted to determine the fate and effects of this waste stream (Adams et al., 1998; Petrenko et al., 1997, Petrenko et al., 1998; Carvalho et al., 2002; Parnell, 2003). In general, the fate of municipal wastewater discharged into coastal waters is dependant on the design and placement of outfalls and the ambient circulation of the receiving environment (Parnell, 2003). The magnitude of coastal pollution can be controlled through the use of proper treatment and disposal methods; however, there are still areas of Canada, such as coastal Newfoundland, where the waste is directly discharged into the ocean.

Environmental Effects

There can be physical, chemical and biological impacts as a result of discharging municipal wastewater in the coastal environment. The effects and impacts can be as diverse as the range of components in municipal wastewater effluent (Table 1.4). The severity of these impacts can depend upon a variety of physical and biological processes coupled to concentration, content, and mixing capability of the wastewater with

surrounding water masses (Petrenko et al., 1997). Environmental impacts may arise from an increase in nutrient loads, decreased levels of dissolved oxygen, and releases of toxic substances, many of which can bioaccumulate and biomagnify in aquatic wildlife (EC, 2001). Acute and cumulative effects on the receiving ecosystem have been identified as a result of the deposition of both treated and untreated municipal wastewater. Acute impacts may result from high levels of ammonia and chlorine, high loads of oxygen-demanding materials, or toxic concentrations of heavy metals and organic contaminants from treatment plant effluents. It is noted that this type effluent is a leading source of the BOD, TSS, nutrients, organic chemicals, and metals that are discharged into Canadian waters (EC, 2001).

Table 1.4 Components of municipal wastewater (EC, 2001)

Type	**Category**	**Examples**
Biological	Bacteria	Fecal coliform (e.g. *Escheria coli*, *Compylobacter*) Viruses (e.g hepatitis A virus) Protozoa (e.g. *Giardia, Cryptosporidium*)
Chemical	Nutrients	Phosphorous Nitrogen (e.g. nitrate, nitrite, ammonia)
	Organic chemicals	Pesticides (e.g. toxaphene, DDT/DDE) Surfactants (e.g. nonylphenol) Chlorinated solvent (e.g. tetrachloroethylene, tricholorethylene) Polycyclic aromatic hydrocarbons (PAHs) Polychlorinated biphenyls (PCBs) Endocrine-disrupting substances (PCBs, dioxins, furans, contraceptives, nonylphenol)
	Inorganic chemicals	Metals (mercury, cadmium, copper, iron, lead, nickel, zinc) Chloride and chlorine Cyanide
	Oil and grease BOD	
Physical	TSS Debris/Grit	

Conversely, as pollutants accumulate in sediments and biota over time, they become more toxic leading to chronic or cumulative effects through bioaccumulation. Some chemicals posing the greatest risk may include PCBs, dioxins and furans, organochlorine pesticides, and mercury and other heavy metals (EC, 2001).

In order to mitigate the effects of the municipal wastewater effluent, several treatment methods have been developed. There are four levels of treatment for municipal wastewater: none, primary, secondary, and tertiary treatment. In cases where no treatment is carried out on the waste, the assimilative capacity of the receiving environment will be relied upon to disperse the waste. It is noted by Sharp (1991) that through proper outfall design, elaborate treatment methods may not be required for areas where the cost and technical skills are too prohibitive. Therefore, in some cases a well-designed outfall may be sufficient if ambient conditions are ideal. BOD values are less for sewage discharged directly into the sea because the majority of freshwater bacteria will die soon after being discharged into the saltwater (Beer, 1997). Primary treatment removes at least 30% of TSS and BOD by sedimentation and filtration through screens and settling tanks. If chemically enhanced primary treatment is available, it can remove 60 to 82% of TSS and 45 to 65% of BOD through coagulation and flocculation (Parnell, 2003). At least 85% of TSS and BOD can be removed by the biological oxidation processes that are involved in secondary treatment. However, inorganic nutrients are products of the biological oxidation of marine algae therefore tertiary treatment can be used to reduce the concentration of inorganic nutrients resulting from secondary treatment.

The various stages and methods available for the treatment of municipal wastewater are outlined in Figure 1.4 while selected concentrations of some pollutants and the treatment effectiveness are given in Table 1.5.

The percentage of the municipal population on sewers served by wastewater treatment in Canada has increased from slightly more than 70% in 1983 to 97% in 1999. However, more than 45% of the communities with sanitary sewers in Atlantic Canada are without treatment facilities (EC, 2001). These communities rely on the natural assimilative capacity of the coastal environment to stabilize the waste. Figure 1.5 indicates the level of treatment for municipal wastewater in Canadian coastal and inland receiving waters in 1999.

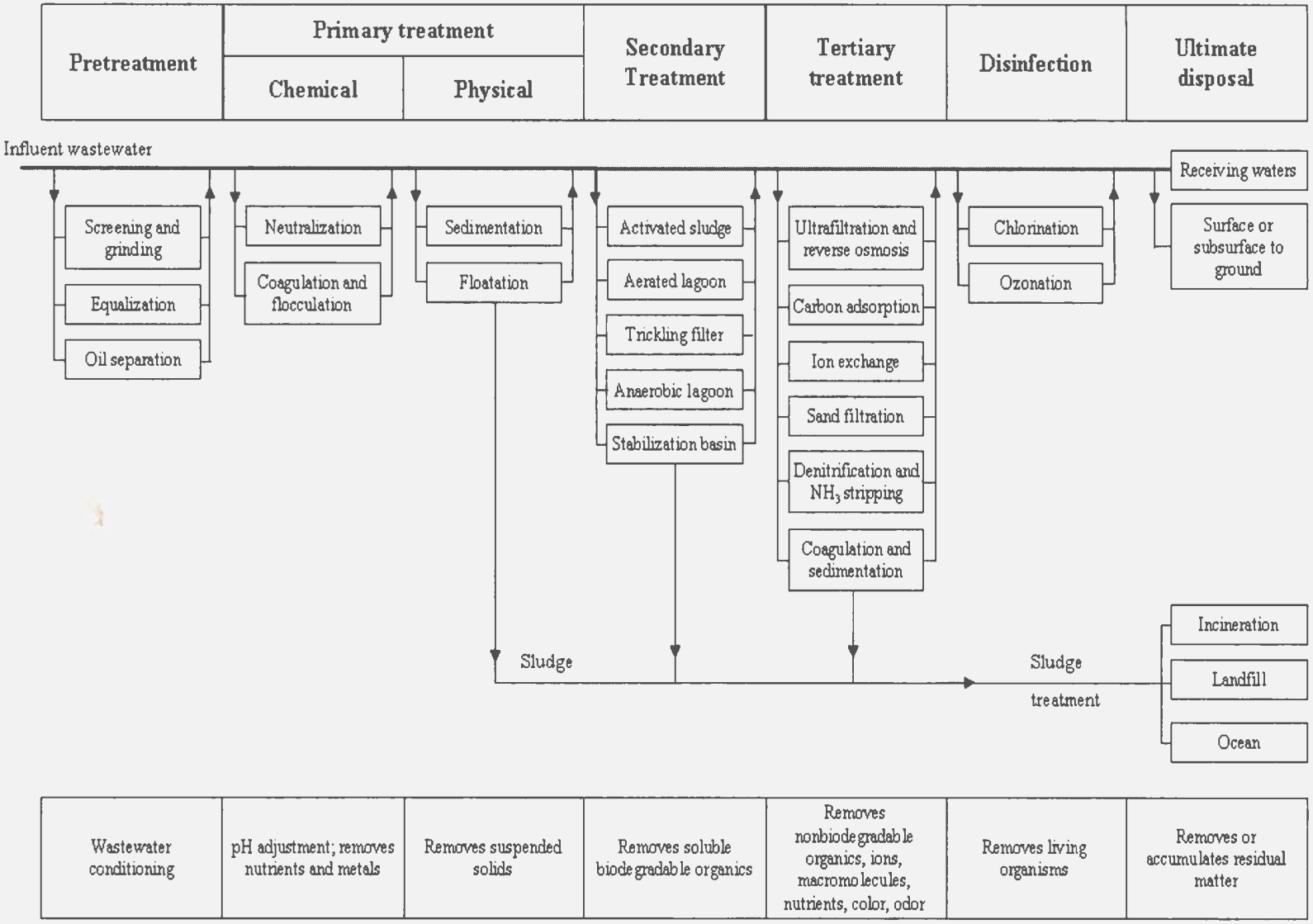

Figure 1.4 Possible wastewater treatment methods and their sequence (Sundstrom and Klei, 1979)

Table 1.5 Typical composition of domestic wastewater (Sundstrom and Klei, 1979)

Parameter	Concentration (mg/L)		% Removal	
	Range	Typical	Primary	Secondary
Solids: Total	300-1200	700		
Settleable	50-200	100	90	
Suspended, total	100-400	220		50-90
Suspended, volatile	70-300	150		60-90
Dissolved, total	250-850	500		5
Dissolved, volatile	100-300	150		30
Organic carbon				
BOD_5	100-400	250	10-30	>90
COD	200-1000	500	10-30	70-80
TOD	200-1100	500	10-30	70-80
TOC	100-400	250	10-30	60-80
Nitrogen				
Total (as N)	15-90	40		35
Organic	5-40	25	40	50-80
Ammonia	10-50	25		0-20
Nitrites			Produced	
Nitrates			Produced	
Phosphorus				
Total (as P)	5-20	12	0-15	20-40
Organic	1-5	2		
Inorganic	5-15	10		
pH	7-7.5	7.0		
Calcium	30-50	40		
Chlorides	30-85	50		
Sulphate	20-60	15		

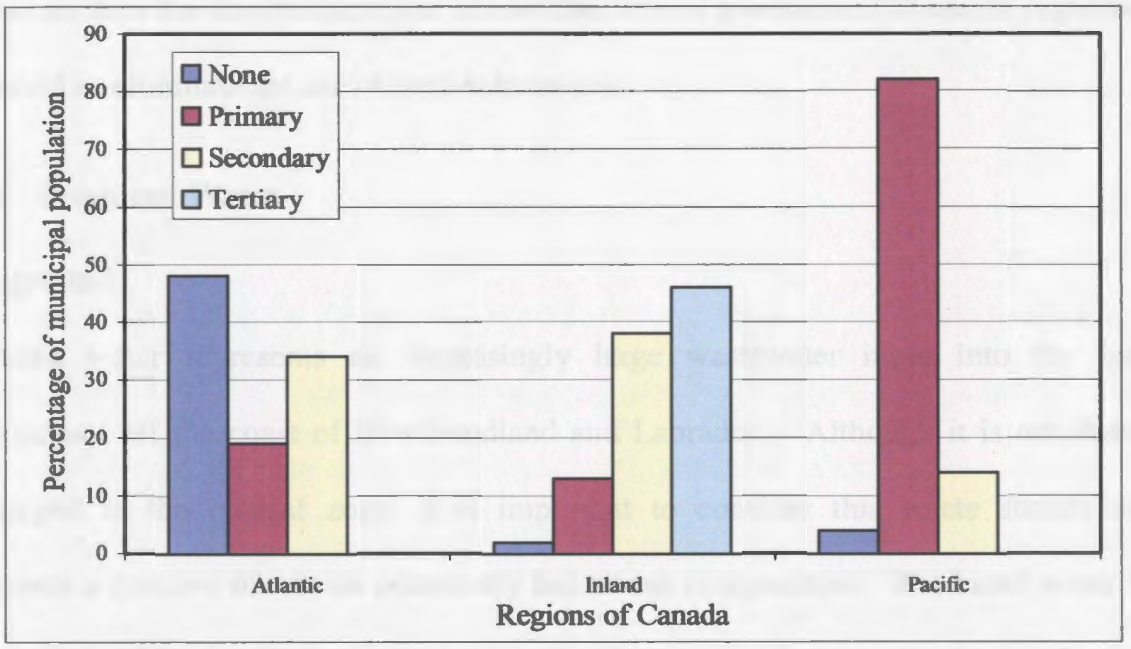

Figure 1.5 Treatment of municipal wastewater in Canadian regions in 1999 (EC, 2001)

Note: Discharge into coastal versus inland (fresh) water is self-reported. The Atlantic coastal waters include discharge to the St. Lawrence estuary. Figures based on municipalities serviced by municipal sewer systems.

Regulatory Review

All levels of government are responsible for the management of Canada's municipal wastewater effluent. Municipal governments have the greatest responsibility for the management of its waste products. The regulation of the municipal sewage treatment operation is the responsibility of the provincial or territorial government. There is a cost sharing agreement between the municipal and provincial governments for infrastructure projects and there is no current legislation relating directly to the disposal of sewage that outlines the federal responsibility. However, there are two acts that may be applicable to municipal wastewater, similar to that of the disposal of fish plant effluent. The *Fisheries Act* has a provision against the release of a "deleterious substance" into waters frequented by fish. The *Canadian Environmental Protection Act* prohibits the release of toxic

substances into the environment and allows the federal government to create regulations to control or eliminate the use of such substances.

1.2.3 Produced Water

Background

Produced water represents an increasingly large wastewater input into the ocean environment off the coast of Newfoundland and Labrador. Although it is not directly discharged in the coastal zone, it is important to consider this waste stream as it represents a concern due to its potentially hazardous composition. Produced water is a combination of the ancient sea water trapped with the oil and gas under the sea floor and the water that is injected to enhance recovery of oil and gas from the formation (Neff and Sauer, 1996). As an oilfield ages, the amount of produced water formed will increase. Cumulatively, the Newfoundland and Labrador offshore industry has produced an estimated 14,157,889 m^3 or 89,050,439 bbls of produced water since 1999 (CNLOPB, 2005). Produced water is the largest waste stream on an oil and gas platform. Of this wastewater, it is estimated that 7,500 to 11,500 tonnes of petroleum hydrocarbons enter the environment worldwide (Holdway, 2002).

The composition can vary considerably according to the formation type, secondary recovery processes and the types of chemicals that are added to enhance recovery of the oil (Ayers et al., 2001). Holdway (2002) observed that due to the variety of chemicals and range of concentrations possible, it is difficult to generalize about the toxicity of produced water. Research involving the examination of produced water's transport, fate and biological effects from oil and gas platforms is increasing. Models suggest that

produced water discharge will be rapidly diluted and dispersed when discharged into the ocean. However, real data with which to confirm these statements is inadequate (Mukthasor, 2001).

Environmental Effects

Little knowledge exists on the fate of the various components of produced water and the possible chronic effects of natural components that have the lowest degradation rates and the highest potential for accumulation such as polyaromatic hydrocarbons (PAHs) and alcylated phenols (Furuholt, 1996). It has been shown that measurable concentrations of two- to five-ring PAHs are discharged with produced water but typically reach near background levels a short distance from the discharge point (Røe Utvik et al., 1999). The most abundant hydrocarbons in produced water are one-ring aromatic hydrocarbons, benzene, toluene, ethylbenzene, and xylenes; however, PAHs are present and pose the greatest concern to the environment (Neff and Sauer, 1996). There is potential for bioaccumulation in local organisms and possible biomagnification in the marine food web from concentrations of toxic chemicals (Chowdhury et al., 2004). It is also possible that human consumers may be at risk from fishery products due to discharges of non-polar organic chemicals such as petroleum hydrocarbons that accumulate in the food web (Neff and Sauer, 1996). Several characteristic organic components of produced water are shown in Table 1.6.

Table 1.6 Organic Components of Produced Water (Ayers et al., 2001)

Component	North Sea Data (mg/L)	US Data (mg/L)	Hibernia Prediction (mg/L)
Total Oil (grav)	2-220	2.3-359	35
Dissolved Oil	≤760	≤200	
Benzene	0.4-5 oil 0.3-440 gas	0.18 –14.0	3.5
Toluene	0.01-2 oil 4-145 gas	0.16-7.95	2.5
Xylene	0.1-7 oil 0.8084 gas	-	0.5
Ethylbenzene	-	0.025-0.56	0.3
Naphthalenes	0.07-0.1	0.018-0.30	0.1
2,4-Dimethylphenol	-	0.016-0.57	0.1
Phenol	2-23	0.20-3.4	1.0
TOC	-	88-661	300
COD	130-15,800	182-3,000	-
BOD	28-6700	126-1920	-

Heavy metals found in produced water can pose concerns to the ecosystem and human consumers of fishery products. In many cases, marine species cannot process metals, therefore they are ingested and retained in their systems resulting in the potential bioaccumulation of toxic chemicals. Some metals characteristic to produced water are given in Table 1.7. It was found that concentrations of most metals in natural marine food webs show either no relation, or an inverse relation to trophic level, thereby indicating that food chain biomagnification of inorganic metals does not occur (Ayers et

al., 2001). However, exploration and production is increasing and the cumulative impact may result in future concerns if they are not closely monitored.

Table 1.7 Comparisons of Heavy Metals in Produced Water (Ayers et al., 2001)

Metals	Gulf of Mexico	North Sea Oil Platforms	North Sea Gas Platforms	Venture	Copan
Arsenic	<0.11-320	0.004-12	<1-100	90	-
Barium	1.0-650,000	-	-	13,500	-
Cadmium	0.06-98	<0.0005-94	<2-490	<10	2-6
Chromium	<0.01-390	<0.001-11	4-220	10	80
Copper	<0.05-210	<1-100	10.0-55	137	8-2,400
Lead	<0.08-5,700	<1-400	<1-18,000	<10	8-45
Mercury	0.06-0.19	0.00001-75	<0.2-33	<10	-
Nickel	0.1-1,674	20-95	10-170	40	20-420
Zinc	7.3-10,200	5-35,000	20-150,000	10	90-26,000

Certain ions also can be a concern to the marine environment because they will bind to other ions such as nitrogen and phosphorus that should be biologically available for marine organisms as part of their lifecycles. Once the nutrients bind with the inorganic compounds they can become useless to the ecosystem in terms of their availability and will no longer be part of the biochemical recycling of matter (Pinet, 2000). Table 1.8 represents major ions found in produced water.

Table 1.8 Major ions in produced water (Ayers et al., 2001)

Ion	Hibernia	Avalon	Venture	Piper	Seawater
Na^+	45,473-188,790	27,500	30,000	29,090-26,620	10760
K^-	96-370	991	276	240-486	387
Ca^{+2}	677-6,530	2,536	20,816	1,190-2,670	413
Mg^{+2}	100-686	576	31	626-670	1,294
Ba^{+2}	2.7-21	-	-	28-81	3-50*
Sr^{+2}	86-873	-	-	236-587	8*
Fe^{+2}	0-89	ND	Trace	0.5-15.9	0.9-1.61*
Cl^-	27,169-114,596	48,798	82,831	42,800-47,330	19,353
Br^-	-	-	-	-	87
HCO^{-3}	378-688	567	1,018	210-270	142
SO_4	248-339	260	863	0-50	2,712
CO_3^{-2}	0	0	0	0	-
OH^-	0	0	0	0	-
H_2S	ND	ND	ND	ND	-
TDS	45,926-189,588	81,227	-	69,805-77,950	-
pH	6.4-8.1	7.1	6.1	7.1-6.7	-
Specific Gravity	1.0317-1.1269	1.0563	1.0910	1.0489-1.0236	1.02

Units in mg/L unless otherwise specified by * which represents µg/L

Proponents of the oil and gas industry have determined that produced water will not have a large effect on marine ecosystems due to its ability to reach ambient conditions quickly (Petro-Canada, 1998). Measurements are required both near field and far-field to validate this statement since produced water is thought to undergo several processes such as evaporation, sedimentation, adsorption, chemical oxidation, photo-oxidation and biodegradation before it reaches ambient conditions and no data exists (Patin, 1999).

Most treatment processes will use a form of gravity separation to divide the water from solids and oil. There are several treatment technologies such as hydrocyclones and

centrifuges that utilize this relationship to accelerate the separation process (Ayers et al., 2001). Another type of treatment process is by using barrier separation or filtration when gravity is no longer effective to remove the dissolved organics which can range from 5 to 30 mg/L but can exceed 200 mg/L (Ayers et al., 2001). However, there is no optimal solution for produced water treatment because each platform is different in terms of the type of produced water, size and capacity. Also, as new methods are introduced, the industry will adapt accordingly to ensure the most appropriate technology is used to comply with regulations. There are several stages that are followed on most platforms to treat produced water before discharge (Figure 1.6)

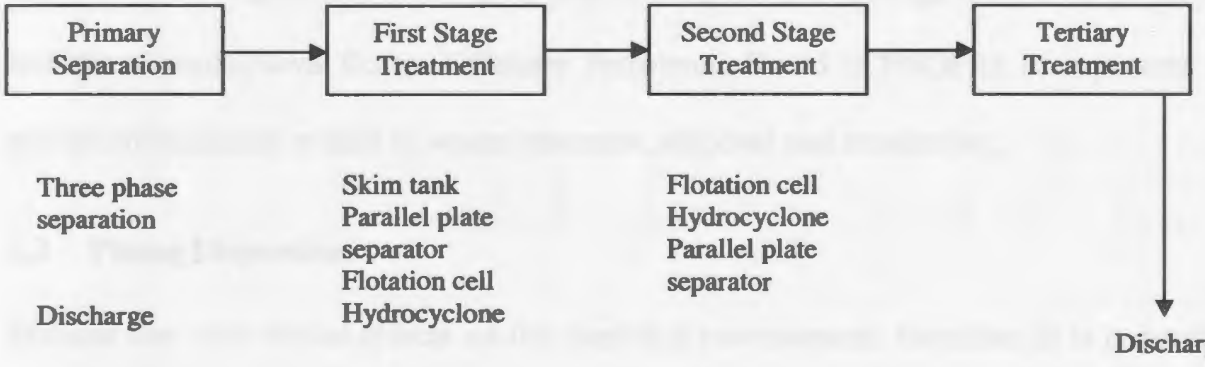

Figure 1.6 Produced water treatment sequence and typical options (Ayers et al., 2001)

Regulatory Review

Several regulatory bodies strictly control the disposal of produced water. The operators of the platforms are strictly monitored to ensure they are meeting all requirements. Regulations and guidelines were developed prior to the first release of any substances into the ocean off Newfoundland as compared to fish plant effluent and sewage where the

practice was well established prior to government intervention even before Newfoundland was part of Canada.

The Canada - Newfoundland and Labrador Offshore Petroleum Board (CNLOPB) is the regulatory body responsible for all aspects of operations in the offshore oil industry in Newfoundland and Labrador. Through its role as the federal-provincial authority, it has the responsibility and authority to evaluate and approve the development and activities of the proponents. With respect to the discharge of waste products from petroleum drilling and production operations in Canada's offshore, a set of guidelines known as the *Offshore Waste Treatment Guidelines* (2002) outlines the recommended practices and standards. The guidelines were prepared by the National Energy Board, the CNLOPB and the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB) to represent the minimum standards related to waste treatment, disposal and monitoring.

1.3 Plume Dispersion

Effluent can have varied effects on the receiving environment; therefore, it is imperative to know its fate once it is discharged thereby allowing for predictions of its extents into the receiving environment. Coastal outfalls are usually designed to maximize the natural assimilative capacity of the ocean to enhance the dispersion of waste and minimize the environmental impact (Carvalho et al., 2002; Economopoulou et al., 2003; Mukthasor et al., 2002). Poorly designed outfalls can cause a build-up of floating debris and sludge deposition which result in an unpleasant, offensive near shore environment as well as the potential for human health hazards. However, a properly designed outfall will disperse the wastes throughout the receiving environment and will ensure the organic matter is

stabilized by natural processes without diminishing the water quality (Sharp, 1991). It is important that dispersion is maximized for the long-term viability of the coastal zone.

Studies on the mixing behaviour of plumes are numerous throughout the scientific literature (Jirka et al., 1996; Huang et al., 1998; Niu et al., 2004; Doneker and Jirka, 2001; Mukthasor et al., 2002; Economopoulou et al., 2003). Most studies involve the measurement of sewage outfalls using tracers to detect the effluent as it disperses through the immediate coastal environment (Ruiz-Beviá et al., 1986; Petrenko et al., 1998; Stacey et al., 2000; Ramos et al., 2002; Zaker et al., 2001; Carvalho et al., 2002; Fong and Stacey, 2003; Parnell, 2003). There are some examples of studies that trace produced water plumes in estuarine and ocean environments (Woodall et al., 1998; Washburn 1999). There are no studies regarding the mixing and hydrodynamic processes of fish plant effluent in the literature to date for the Newfoundland and Labrador region. Plumes in this context have not been well studied and documented. Further, there is no standardization of the design of fish plant outfalls in Newfoundland and Labrador. They are characteristically rudimentary with most discharges consisting of pipes exhausting above water adjacent to a wharf as deemed appropriate by the plant operator.

Numerous physical processes are involved in the distribution of waste in the aquatic ecosystem that range from molecular diffusion to large-scale turbulence (Moore and Gerhardt, 2000). Once effluent is discharged into the marine environment, it undergoes several dilution mechanisms including initial dilution (or near-field), dispersion dilution (or far-field), and effective dilution due to decay of non-conservative substances (Stacey et al., 2000). This process occurs as a result of particle motions due to the turbulence of

seawater. These processes work to carry the pollutants within the effluent away from the discharge location.

Near field mixing refers to the initial mixing that occurs within about 100 m and within a few minutes of release where the initial jet momentum, buoyancy flux, and outfall characteristics control the mixing process (Jirka et al., 1996; Schnurbusch, 2000). The dispersion of the effluent in the near field region is defined by the outfall itself and the properties of the effluent. The greatest rates of dilution are found during this phase (Parnell 2003). This region ends where the discharge turbulence collapses under the influence of buoyancy forces (Doneker and Jirka, 1991; Economopoulou et al., 2003). At this point, the discharge flow encounters a boundary such as a surface, bottom, or density stratification layer (Schnurbusch, 2000). It is at this point when there is a transition to the far field region. There is an interaction with the surrounding medium and the plume becomes a diffuse mass carried along by the ambient current. Ambient conditions that may assist these processes include water hardness, temperature, salinity, acidity or alkalinity, background concentrations of nutrients and metals, and the physical nature of the receiving water body (EC, 2001). The spatial and temporal scales for far field mixing occur within a range of hundreds to thousands of metres from the outfall and from minutes to weeks after discharge (Parnell, 2003). A typical plume dilution schematic is shown in Figure 1.7.

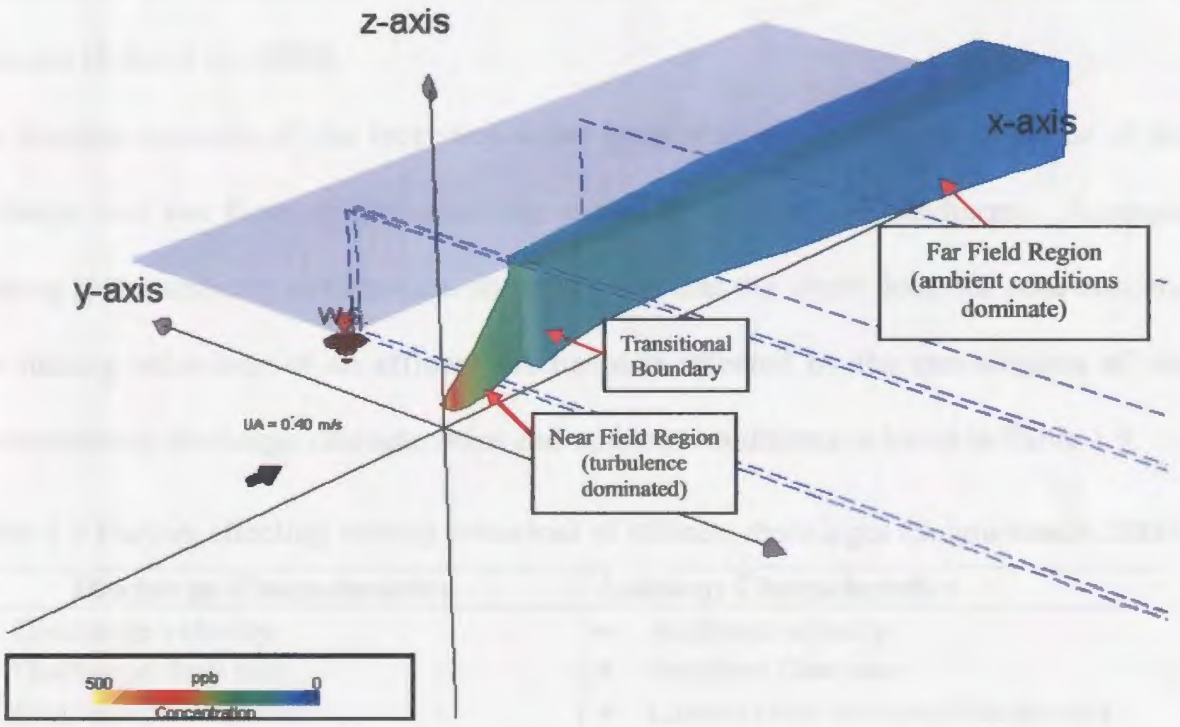

Figure 1.7 Typical plume dilution
Created by author with 3D CorVue, CORMIX GI 4.1 software

Plume behaviour affects the extent of environmental impacts and is partly determined by the configuration of the discharge pipe. Careful consideration should be given to the overall design of an ocean outfall as it is intended to not only dilute the effluent but also to permit the natural processes in the ocean to stabilize the waste with minimal environmental damage (Mukthasor et al., 2002). The geometry of the discharge port and of the receiving water body can vary. The pipe can be configured to be freestanding in open water, or in a bounded area bank-to-bank, bank-attached, or bottom-attached. Bottom-attached and shore-attached plumes are thought to result in greater impacts

because they will dissipate more slowly and have the potential to affect bottom-dwelling creatures (Jirka et al., 1996).

The dilution capacity of the receiving water body also depends on the volume of the discharge and the flow of the receiving water at the point of discharge. Adequate flushing in the ambient environment should ensure that the waste does not pose concern. The mixing behaviour of an effluent discharge is affected by the combination of two characteristics: discharge characteristics and ambient conditions as listed in Table 1.9.

Table 1.9 Factors affecting mixing behaviour of effluent discharges (Schnurbusch, 2000)

Discharge Characteristics	Ambient Characteristics
• Discharge velocity • Discharge flow rate • Port or pipe diameter • Diffuser/port configuration and geometry • Elevation of port or pipe off the bottom • Density of the discharged fluid	• Ambient velocity • Ambient flow rate • Lateral cross sections/bathymetry • Ambient density profile

Low hydrodynamic energy conditions can limit the volume and flow of receiving water and will determine its ability to dilute or assimilate effluent discharges thereby affecting the extent of toxic effects occurring in the vicinity of the discharge (EC, 2001). Concentrated effluent may be highly lethal in laboratory tests, but if the receiving systems have a large assimilative capacity the effluent may dilute so that it is no longer harmful (EC, 2001).

Mathematical models such as in Mukthasor (2001) have been developed to predict the near field behaviour of plumes. Another example of a dispersion model is the Cornell Mixing Zone Expert System (CORMIX GI version 4.1). The model has been developed

into a software system designed to incorporate several hydraulic models (Davis, 1999) for the analysis, prediction, and design of aqueous toxic or conventional pollutant discharges into diverse water bodies (Jirka et al., 1996). The system is sub-divided into several modules: submerged single port discharges (CORMIX1), submerged multiple port discharges (CORMIX2) and surface discharges (CORMIX3). By inputting the ambient conditions and the discharge, effluent and mixing zone data, it is possible to obtain dilution and concentration predictions as a pollutant moves through the mixing zone, away from the source.

In situ measurements of an actual waste field are critical to evaluate these models in order to ensure their accuracy. These types of validation experiments are difficult to conduct due to the high costs, variability of discharge flow rate, currents and stratification and the large aerial extent to be monitored (Carvalho et al., 2002). In order to effectively trace and map a plume, it is important to understand the effluent characteristics to best direct the study. The composition of the waste stream and its properties are just as important as the discharge characteristics in the planning stage of a plume study. A detailed discussion on sensor technologies for tracing experiments will be given in Chapter 2.

1.4 Objectives and Scope of the Study

As previously mentioned, the environmental effect of effluent plumes can vary considerably. Fish plant effluent is not well studied, especially in the Newfoundland and Labrador region. Sewage outfalls receive more attention as they are common throughout the world as a necessity to human development. Produced water has been well researched and represents an identified hazardous substance to the surrounding

ecosystem. In general, sampling and monitoring methods have not changed considerably over time despite the ever-increasing level of technology. This study provides an overview of several parameters that should be considered when studying effluent plumes for the determination of their fate in the coastal zone. An experiment was conducted to determine the effectiveness of using several selected parameters to measure the extent of a fish plant effluent plume. Further, it compares the measured data with a predictive plume model to determine if it can be used in this context.

1.5 Thesis Overview

Chapter One provides pertinent background information on different types of effluent present in Newfoundland and Labrador. It also discusses previous work conducted in the areas of fish plant effluents and review of plume dispersion. Chapter Two identifies some sensing technologies that can be utilized in conjunction with autonomous underwater vehicles (AUVs) for tracing of effluent plumes. The experimental design and apparatus is described in Chapter Three. Chapter Four details the results of the tests completed at a seafood processing plant. Chapter Five presents a discussion of the results and formulates some comparisons within the experimental results and against a predictive model. Finally, in Chapter Six conclusions are drawn and recommendations are made for further study in this area.

Chapter 2 Monitoring Effluent Plumes

2.1 Monitoring Platforms

Traditional Methods

Traditionally, the chemistry of marine environments has been characterized by using wet chemical analysis of bulk water collected with large volume samplers (Petro-Canada, 1998). Specially designed sampling bottles are deployed along with other instruments to obtain a vertical profile of the water column at several pre-specified locations. From a survey vessel, discrete water samples are obtained using scuba divers to physically collect the sample or a pump with a bottom-weighted hose. In deep water (beyond scuba depth), the sampling protocol may include the use of samplers with polyethylene bottles attached to a hydrowire and lowered into the sea with a winch.

These processes can be time consuming, expensive and could yield inaccurate results depending on the parameter in question since the operator is at the surface. Furthermore, several parameters such as temperature can change rapidly when the sample is brought to the surface. Sample cross-contamination is another issue that could be a concern as several samples would be taken from the same hose. Although these discrete sampling approaches yield a general impression of the chemical environment, large sample volumes restrict their ability to describe conditions within specific micro-environments such as hydrothermal vents (Di Meo et al., 1999). Conceivably, storage and transportation of potentially hundreds of bottles could lead to mix ups and a greater probability of complications.

Degradation of the samples over time has also been identified as a major concern depending on the length of cruise and analysis facilities. Laboratory procedures usually include sample analysis by a gas chromatograph with quantification by mass spectrometer for chemical analyses (Neff and Sauer, 1996). Off-site measurements by university, provincial, federal and private laboratories are still the primary method for environmental analysis of nutrients and other chemicals. There is a recognized need for enhanced on-site measurement capabilities and particularly for high-resolution chemical sensors and analyzers that operate *in situ* (Hanson and Moore, 2001).

Regulations imposed by authorities may require observation of the physical and chemical nature of the receiving environment as part of an effects monitoring program. Parameters of importance could include current direction and speed, temperature, conductivity, salinity, dissolved oxygen, pH and fluorescence. These parameters, in most cases, should be measured *in situ* to ensure that the readings are accurate and reliable. For example, it is not feasible to estimate the salinity or temperature from a ship and anticipate an accurate reading of its exact location compared to measurements taken at the source. Typical requirements of some oceanographic sensors are shown in Table 2.1.

Table 2.1 Typical requirements for *in situ* sensors (Varney, 2000)

Parameter	**Typical Range**	**Accuracy**	**Resolution**
Temperature	-5 to 30°C	0.005°C	0.001°C
pH	3.5 to 9.5 pH	0.01 pH	0.001 pH
Conductivity	0 to 65 mS cm^{-1}	0.002 mS cm^{-1}	0.001 mS cm^{-1}
Redox (Eh)	-400 to +600 mV	1 mV	0.01 mV
Chloride	1 to 14 pCl	0.01 pCl	0.001 pCl
Dissolved Oxygen	0 to 500%	1%	0.1%
Chlorophyll *a*	0 to 100 mgCdm^{-3} (AUF)	0.01 AUF	0.01 AUF
Sulphide	1 to 14 pS	0.01 pS	0.001 pS

These requirements indicate a general summary of expectations of some parameters. The range requirements will vary given the application, but in general, the greater the range the more versatile the sensor. Accuracy of the sensor refers to the ability to obtain the actual value of the parameter, i.e. how close to the measurement is possible. For example, if one were to obtain a temperature measurement of 10.844°C using a sensor with an accuracy rating of 0.005 °C, the actual measurement is 10.844 ± 0.005°C. The resolution of an *in situ* sensor refers to the precision of the measurement or the incremental change of the instrument. With respect to the above example, measurements can be obtained for every 0.001°C in change of temperature for a resolution of 0.001°C.

Sensor Platform Alternatives - AUVs

As previously mentioned oceanographers and scientists have relied on traditional sampling techniques such as grab samples, divers and towed sensor packages to obtain information about water quality. *In situ* platforms are being developed and used to enhance the capability of the oceanographic scientific community to provide improved temporally and spatially accurate data. One such type of platform beginning to be employed is the autonomous underwater vehicle (AUV), defined as a self-propelled submersible robot capable of carrying out pre-programmed tasks without human intervention (Sadiq et al., 2002). AUVs have undergone several transformations in purpose, size, propulsion modes and duration capabilities (Yu et al., 2002). First used in military applications such as mine detection, their use in the scientific community has expanded with improvements in sensor technology and miniaturization (Field et al., 2002). They are useful for environmental monitoring to give accurate continuous, *in situ*

data which can be used for delineating plumes as they provide an excellent platform for mounting scientific payloads. Based on mission requirements, an AUV would have the ability to detect and map a waste stream as it disperses and dilutes in the water column. This information could be used to show cause and effect relationships, validate dispersion models, and develop or enhance guidelines for treatment of wastewater.

One example of an AUV is "C-SCOUT" (Canadian Self-Contained Off-the-shelf Underwater Testbed) developed jointly by Memorial University of Newfoundland and National Research Council of Canada - Institute of Ocean Technology (NRC-IOT) as part of a Natural Sciences and Engineering Research Council (NSERC) Strategic Project entitled "Offshore Environmental Monitoring Using AUVs" from 1999 to 2004. The project studied the development and use of AUVs for environmental monitoring of produced water from the offshore oil and gas industry. C-SCOUT has a modular design which would enable the use of a variety of sensors as a scientific payload. The baseline configuration of C-SCOUT is 2.7 m long and has a diameter of 0.4 m. Figure 2.1 depicts C-SCOUT during a testing procedure in the Ocean Engineering Basin at NRC-IOT in St. John's Newfoundland.

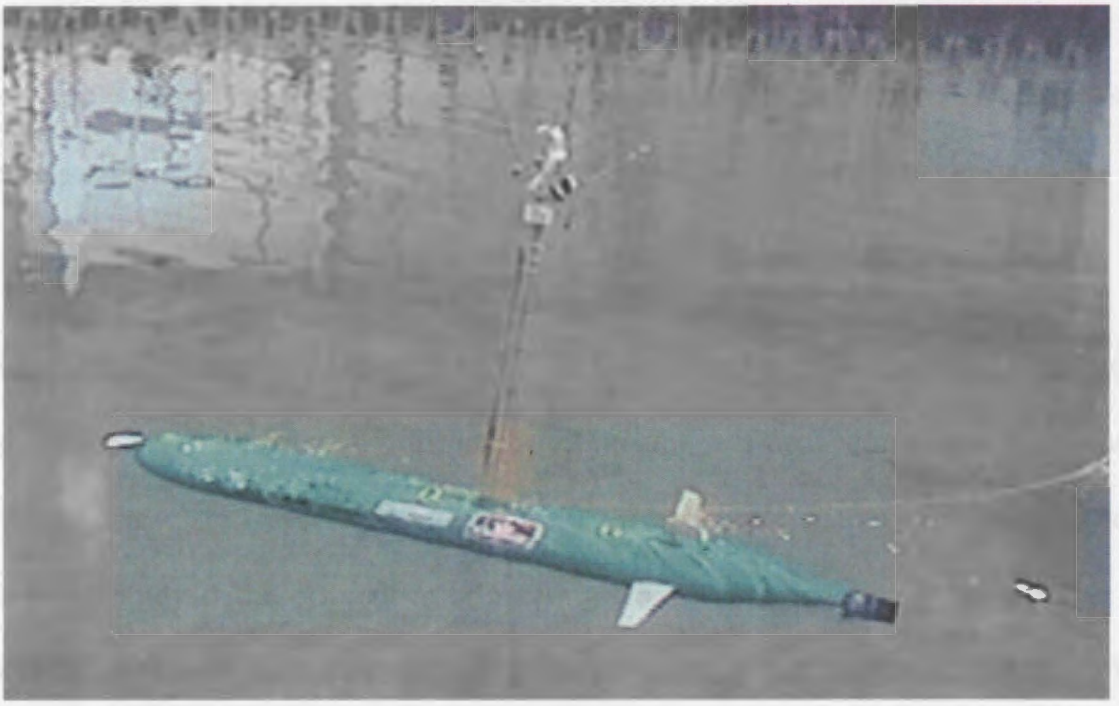

Figure 2.1 C-SCOUT in the water

To trace an effluent plume as it travels through the water column, parameters of interest are selected and appropriate sensors are integrated into an AUV. Adding dye or an approved chemical to the effluent is an accepted method for tracing plumes as the chemical takes on the physical characteristics of water molecules from the effluent (Turner Designs, 2004). Depending on the budget and purpose of the experiment, several sensors can be used to follow the effluent through the water column with the only limitations being detection limits and equipment or platforms available. Many studies use multiple parameters to measure the oceanographic conditions around outfalls to obtain information during the field tests (Petrenko et al., 1997; Petrenko et al., 1998; Carvalho et al., 2003; Parnell, 2003). This method is justified since field costs can be high, so it is advantageous to obtain as much information as possible which can be disseminated later. Field costs can include ship time, personnel, and equipment. The

following section reviews potential parameters of interest for oceanographic study and several viable sensing technologies that have been used in monitoring programs with AUVs as a sensing platform.

2.2 Physical sensors

Certain physical parameters are ideal to use in plume tracing experiments if it is known that a particular parameter is different within the effluent compared to ambient conditions. These are known as natural tracers. For example, salinity would be an ideal parameter to study if the effluent is originating from a desalination plant (Zaker et al., 2001) or temperature for a thermal electricity generating station (Laval, 1997). This method negates the requirement for the addition of more chemicals to a potentially compromised environment. Other parameters that could be used in natural tracer mapping can include turbidity, dissolved oxygen and pH (Parnell, 2003).

2.2.1 Salinity

Salinity is referred to as the total ion content of the water at a given temperature (Pinet, 2000). The ions come from a complex mixture of dissolved salts that naturally occur in the ocean. Sodium chloride is the most common of all the major dissolved salts with sodium bicarbonate, sodium sulphate, magnesium, calcium and potassium chlorides and sulphates composing the remainder (Beer, 1997). The typical ionic composition of seawater is shown in Table 2.2. The current definition of salinity (Lewis, 1980) is based on the electrical conductivity. Conductivity is a measure of the water's ability to transmit an electrical current which is directly proportional to salinity; therefore, pure water with a

salinity of zero has no conductivity. This measure is used to ensure there is an international standardized value. Previous to 1978, there were several standard values which lead to difficulties in determining any ocean circulation models or in the comparison of data (Lewis, 1980).

Table 2.2 Concentrations of the major constituents in surface seawater (Pilson, 1998)

Ion	mg $kg^{-1}S^{-1}$	At salinity: S=35 PSU		
		g/kg	Mmol/kg	mM
Na^+	308.0	10.781	468.96	480.57
K^+	11.40	0.399	10.21	10.46
Mg^{++}	36.69	1.284	52.83	54.14
Ca^{++}	11.77	0.4119	10.28	10.53
Sr^{++}	0.227	0.00794	0.0906	0.0928
Cl^-	552.94	19.353	545.88	559.40
SO_4^-	77.49	2.712	28.23	28.93
HCO_3^-	3.60	0.126	2.06	2.11
Br^-	1.923	0.0673	0.844	0.865
$B(OH)_3$	0.735	0.0257	0.416	0.426
F^-	0.037	0.0013	0.068	0.07
Total	1004.81	35.169	1119.87	1147.59
Water		964.80	53 555.0	54 881.0

By definition, a solution with a salinity of 35 in Practical Salinity Units (PSU) has a chlorinity equal to 19.374×10^{-3} (Beer, 1997). It is noted that in coastal regions, seawater can have a low salinity ranging from 0 to 20 PSU (UN Atlas of the Ocean, 2005) with lower salinity values occurring near freshwater rivers and streams. Areas with extreme rainfall conditions (high or low) can have extreme values of salinity.

It has been suggested (Woodall et al., 2001) that salinity stratification can be used to track plumes such as produced water outfalls. Salinometers are used to measure the salinity in seawater. In general, these sensors operate by measuring the conductivity in water compared to a calibrated solution and calculating the value given the observed

temperature and depth. One problem with this method is that electrical conductivity of seawater has a strong dependence on temperature. Therefore, the measurement of temperature is crucial to the accurate measurement of both parameters (Pilson, 1998).

2.2.2 Temperature

Temperature can be used to locate certain of wastewater plumes in addition to being useful in salinity calculations. Laval (1997) used an AUV to map the effluent plume being discharged from a thermal generating station. Temperature is critical in thermoregulation of the ocean. A thermal plume can be considered a pollutant because warm water contains less dissolved oxygen than water at lower temperatures and at temperatures above 37°C, few plants and animals are able to survive (Beer, 1997). The average temperature of the surface of the world ocean is approximately 17.5°C. The highest temperatures (>35°C) are found in the Red Sea while the lowest (<- 2°C), has been observed in the Weddell Sea (UN Atlas of the Ocean, 2005).

Measurement of temperature can be applicable to an effluent plume whose temperature is significantly different than that of the ambient conditions. The measurement of temperature is a straightforward procedure, requiring a digital thermometer and recording device. Thermistors are used in the measurement of temperature *in situ*. The instrument is composed of semiconductor material which exhibits a large change in resistance proportional to a small change in temperature (Wallener, 2005).

Salinity and temperature are the two physical quantities that should be determined in any scientific investigation of the ocean (Beer, 1997). With these parameters, other characteristics such as density can be determined whose measurement is critical in the

determination of the stability and flow characteristics of the water. Density is influenced principally by the temperature, dissolved salt content of water and depth. Figure 2.1 represents a temperature-salinity diagram which shows the unique relationship between the parameters. Along each isoline, one can find the same density given the particular temperature and salinity values determined through measurement.

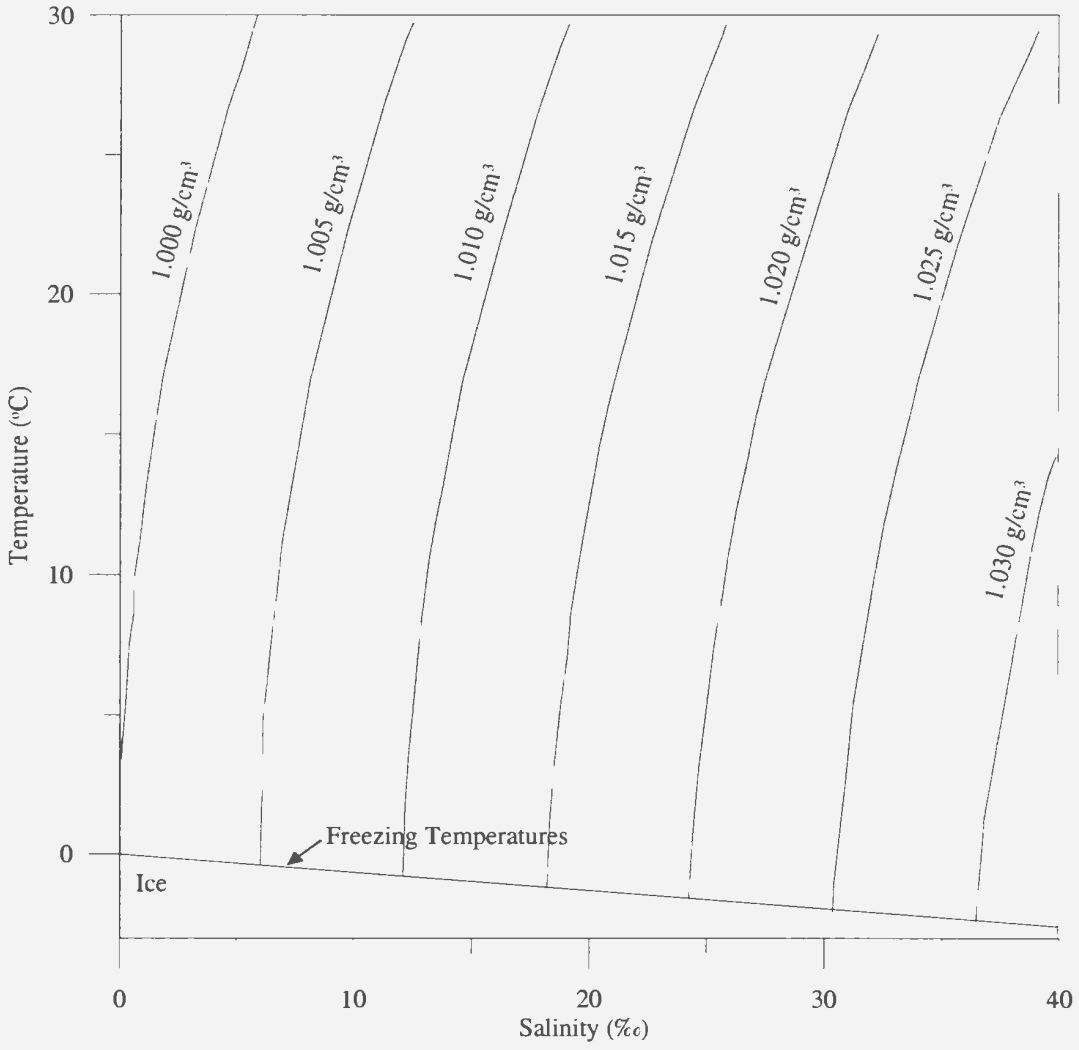

Figure 2.2 Temperature-Salinity Diagram (Pinet, 2000)

An apparatus that incorporates these parameters into one instrument is known as a CTD (conductivity, temperature and depth or pressure). CTDs have become commonplace within the oceanographic community. There are numerous examples of studies which deploy such sensor technology as part of their monitoring program (Bales, 1996; Laval, 1997; Parnell, 2003; Petrenko et al., 1998; Carvalho et al., 2002; Woodall et al., 2001; Washburn et al., 1999; Yu et al., 2002). These devices are typically lowered into the water column at specified depths and towed through an area behind the vessel. The CTD either stores the data within the sensor's memory or it transmits electronic signals to the ship where they are stored in a shipboard computer for later analysis. CTDs have been miniaturized to make them accessible for use with underwater vehicles to test for these parameters as the vehicles travel through the water column. These sensors have also been adapted to interface with other physical parameters such as pH, dissolved oxygen and turbidity. Parameters such as sound velocity and water density are calculated from the basic configuration of a CTD.

2.2.3 Dissolved Oxygen

Another physical parameter that can be valuable in the study of effluent plumes is dissolved oxygen (DO) which is critical to the survival of aquatic ecosystems. By studying the DO initial assessments of the ambient water quality and primary production can be made which are crucial to ecosystem health (Sharp, 1991; Rudolph et al., 2002; Armudala et al., 2004). Oxygen normally enters the ocean through the atmosphere, usually in polar regions and is also produced by photosynthesis in phytoplankton in the

upper layers of the sea (UN Atlas of the Ocean, 2005). Photosynthesis is the chemical process that plants use to convert carbon dioxide into oxygen in the presence of light as follows:

$$6CO_2 + 6H_2O \xrightarrow[light]{} C_6H_{12}O_6 + 6O_2 \qquad [1]$$

Extreme low values arise where wastes such as sewage pollute coastal areas and induce high levels of BOD due to high bacterial activity. The solubility of oxygen in water depends upon salinity, temperature and pressure, therefore a CTD is usually deployed with a DO sensor (EC, 2001). It is generally observed that surface waters are near saturation or equilibrium while the first several metres are supersaturated. In this region, plant material can effectively perform photosynthesis to create more oxygen. As one moves down the water column, the amount of oxygen decreases considerably. In the deep ocean, oxygen demand is limited; but oxygen concentrations are relatively uniform but well below saturation. Areas of low oxygen are known as anoxic and areas where no oxygen is present are known as hypoxic.

Seawater has a normal range of 7 to 14 mg of O_2 per kg of water (Beer, 1997). The concentration of DO is usually expressed in milligrams of oxygen per litre of water (mg/L) or parts per million (ppm). Some DO sensors compare calculated oxygen content with observed concentration and report percent saturation (% sat.) which is calculated using Equation [2].

$$\% \text{ Saturation} = 100 \times DO / (DO)_s \qquad [2]$$

where DO is the observed value and $(DO)_s$ is the saturation value determined through calibration prior to deployment (Beer, 1997).

The amount of oxygen that a given volume of water can retain is a function of the atmospheric pressure at the water-air interface, the temperature of the water, and the amount of other dissolved substances (Global-Spec, 2005). Dissolved oxygen sensors generally consist of a thin organic membrane that covers an electrolyte and two metal electrodes. As water passes through the sensor, oxygen diffuses through the membrane at a rate proportional to its partial pressure. The two types of sensors for measuring dissolved oxygen are known as galvanic and polarographic. In both cases, an electrode is used to produce a current where the dissolved oxygen reacts with the cathode. The main difference between the probe types is that polarographic probes require an external potential voltage whereas galvanic probes do not have this requirement (Global-Spec, 2005).

2.2.4 Total Solids

The measurement of particulate matter from effluent plumes can be very important in an assessment of water quality in a receiving environment. Total suspended solids (TSS) have been found to be high in fish plant effluent and municipal wastewater. Several adverse effects can result from the injection of a large amount of particulate matter into a receiving environment. The overall water will be diminished in terms of water clarity and sedimentation. The suspended solids can also be responsible for the transport of adsorbed contaminants. Poor water clarity can cause a reduction of photosynthesis and plant growth as the light can not penetrate to the ocean floor where flora and fauna reside. Finally, solids can reduce the growth or survival of species by blanketing spawning grounds and smothering shellfish beds (EC, 2001). Particulate matter from effluent can

be termed total solids (TS) which are classified according to their size and solubility as total suspended solids (TSS) or total dissolved solids (TDS) as seen in Table 2.3.

Table 2.3 Types of solids (Coastal Zone Research, 2004)

Type	Description
Total Solids	Solids retrieved after evaporation and subsequent drying of the sample between 103 - 105°C (contains fixed and volatile)
Total Suspended Solids	Solids retained by a filter of 2.0 ≤ μm nominal pore size
Total Dissolved Solids	Solids that pass through a filter of 2.0 ≤ μm nominal pore size

TS can be measured by a turbidity sensor. These instruments measure the average volume of light scattering over a defined angular range. Turbidity is an expression of the optical property that causes light to be scattered and absorbed instead of transmitted through a sample. Both particle size and concentration of suspended solids as well as dissolved solids can affect this reading; therefore, the measurement of turbidity can used to determine the amount of suspended solids in the water column.

2.3 Chemical Sensors

There is a wide variety of naturally occurring chemicals in seawater. Seawater naturally contains an array of dissolved minerals, elements and salts. It has been suggested that all known stable elements can be found in sea water although in very small concentrations (Beer, 1997; Pilson, 1998). There are also chemicals that exist in the ocean that are a direct result of human influence. Identification and monitoring of these chemicals can be crucial to ensure that regulations are sufficient and are being followed.

Chemical tracers can be in the form of chemicals introduced through anthropogenic activities (e.g. radioactive tritium and carbon, chlorofluorcarbons, etc.) or by

experimenters (e.g. dyes, sulfurhexafluoride, etc.) (Field et al., 2002). If the substance is not already in the water, it can be added to water or to the waste itself to trace it as it travels through the water column. This technique may be useful if the appropriate sensors are available. An advantage to this type of experiment is the confidence that the background quantities should be negligible. Therefore, a degree of certainty can be obtained in the results. Also, there is no dependency on pre-existing conditions of the area to obtain useful results.

However, the addition of dyes in a plume dispersion study may not yield more accurate results that would to ensure the data would have a better correlation to a model. In some cases, due to uncertainties in the measured dilutions, no definitive conclusions can be made. Patchiness and variability may preclude conclusions about the far field plume behaviour and plume spreading (Carvalho et al., 2002). These techniques are being honed as the technology increases; however, there is much work to be done to obtain reliable field results to correlate to simulation models.

2.3.1 Dye Tracers

Dyes can be used to mimic the movement of water molecules and substances transported by the water resulting in the ability to conduct plume dispersion experiments at different scales from the laboratory to the ocean. Rhodamine WT (RWT) is a common dye tracer that is used for effluent monitoring programs (Adams et al., 1998; Stacey et al., 2000; Parnell, 2003; Farrell et al., 2003). RWT was originally developed for the measurement of time of travel of solutes in streams but its use has expanded to include other experimental methods (YSI, 2004). RWT is preferred for most dye fluorometry

hydrologic studies due to its ease of use, relatively low cost, low adsorptive tendency, strong fluorescence, high diffusive properties, chemical stability and benign character in the aquatic environment (YSI, 2004).

Other dyes that have been used in dispersion experiments include rhodamine B (Ruiz-Beviá et al., 1986) and fluoroscein (Carvalho et al., 2002). Pennell (2003) describes the use of dimethyl sulfide (DMS) as a tracer for detection using a mass spectrometer on an AUV. Lithium chloride is another example of a chemical tracer that has been proven to yield useful results in dispersion studies (Girling et al., 2004).

In some cases, it is advantageous to use several dyes as they have various properties that can provide results given variable ambient conditions. Carvalho et al. (2002) conducted field observations by adding Amide-rhodamine G Extra (or Orcacid Sulpho Rhodamine G) and Uranine or Fluorescein Sodium to sewage effluent while obtaining measurements of the oceanographic conditions including measurements of the currents, dissolved oxygen, pH, turbidity, and CTD profiles. Adams et al. (1998) utilized Rhodamine WT and Saturn Yellow Day-Glo fluorescent paint to estimate the residence time within Boston Harbour.

Five to ten percent of all molecules possess a native fluorescence chemical that can be induced to fluoresce by chemical modification (Crompton, 2000). Each chemical emits a different wavelength of light; therefore, one can use this property to determine the chemical composition of a plume. As a result, fluorescence can be used for the determination of not only dyes but also PAHs, carboxylic acids, phenols, amino acids, polychlorobiphenyls (PCBs), nitriloacetic acid, chlorophyll and other plant pigments

(Crompton, 2000). Spectrofluorimetric methods can be used to obtain concentrations as low as one microgram per litre (Varney, 2000). The technique is only valuable if the type of chemical being tested is known because a wavelength separation filter must be present in order to detect that material. Rhodamine WT, for example, has an excitation wavelength of 550 nm. Also, there are several physiochemical factors that may affect the fluorescence of dyes which are listed in order of relative importance: concentration, water temperature, interference, quenching, photochemical decay, sorption, pH and dissolved oxygen (YSI, 2004).

Fluorometers are used to measure dye tracers in seawater. They are designed to measure the amount of fluorescent radiation produced by a sample exposed to monochromatic radiation (Global-Spec, 2005). A fluorometer is usually designed to consist of a source of excitation energy or light, a long-pass wavelength separation filter to separate between the strong excitation light and the fluorescence signal, and a detection device. Usually, the detector is in the form of a photomultiplier tube or a photodiode. A photomultiplier tube multiplies the effect of the light that strikes it and converts photons of light into electrical signals so that the light can be precisely measured. A photodiode is a semiconductor used to detect light and generate an electrical current (Global-Spec, 2005). Light is collected at 90° from the incident light (excitation) direction. The light energy is absorbed by a molecule and then re-emitted again as a photon of light with a slightly longer wavelength. Other names of this class of sensor include luminescence spectrometers, fluorimeters, fluorescence spectrometers or spectrofluorometers (Global-Spec, 2005).

2.3.2 Nutrients

Nutrients are critical to ocean life as they are basic substances essential to all living creatures and plants. Life depends on the availability of carbon, oxygen, nitrogen and phosphorus. Nitrogen is used in amino acids which make up proteins while phosphorus is used in compounds such as adenosine triphosphate (ATP) for energy transfer within organisms (Beer, 1997). However, some nutrients can have detrimental effects to coastal water when discharged in large amounts. Excessive loadings of phosphorus, ammonia, and suspended solids from effluent and bacterial contamination from outfalls contribute to problems of near shore water clarity and poor water quality (Rao and Murthy, 2003). It has been suggested that the most harmful effects of nutrient loading on the coastal environment are due to eutrophication (Parnell, 2003). Eutrophication refers to the process whereby water bodies such as estuaries, harbours, lakes or slow-moving streams receive excess nutrients that stimulate excessive plant growth often called an algal bloom (Parnell, 2003). These plants can include algae, periphyton attached algae, and other nuisance plants or weeds. The increased plant material causes a reduction in dissolved oxygen once the excess plant material dies and begins to decompose (Hanson and Moore, 2001; USGS, 2005). The anaerobic decomposition of the organic matter leads to a breakdown of proteins and other nitrogen compounds releasing hydrogen sulphide, ammonia and methane (Islam et al., 2004).

This cycle can lead to the death of other aerobic organisms in the water column enhancing the effect. The occurrence of eutrophication indicates a system that cannot cope with the available internal or external nutrient inputs (de Jonge et al., 2002). Some

symptoms of eutrophication include turbid and foul smelling water, sea foam, oxygen depletion accompanied by mass mortality of animals and accompanying H_2S production, proliferation of macrophyte algae, development of noxious algal blooms resulting in shellfish poisoning (de Jonge et al., 2002).

The measurement of certain nutrients is an important indicator of ecosystem health, but can also be used to trace the path of an effluent plume such as fish plants, sewage and agricultural operations (Ruiz-Beviá et al., 1986; Parnell, 2003). Although there is wide range of dissolved chemical species in sea water, only a small number can be measured *in situ* by chemical analyzers including nitrite, nitrate, phosphate, silicic acid, hydrogen sulphide, hydrogen peroxide, manganese and iron (Blain et al., 2000). To measure these types of species, colorimetric detection can be used to detect the absorbance of light. The principal is based on Beer's law which links the absorbance (A) of the light to the analyte concentration (C) through the relationship $A = \varepsilon CL$. In this equation, ε is the coefficient of molar absorption related to the chemical structure of the product and function of the wavelength, and L is the length of the flow cell (Blain et al., 2000). This type of analyzer includes several basic components: a light source, a wavelength selector (usually), a flow cell and a receptor transforming the light into an electric signal similar to a fluorometer. These types of nutrient analyzers have been used in conjunction with a transmissometer, a CTD with oxygen, pH and light sensor on a light-weight towed vehicle for tracking and mapping chemical plumes in coastal waters (Hanson and Moore, 2001).

2.3.3 Volatile Organic Compounds

Volatile organic compounds (VOCs) are known to occur naturally in the oceanic environment and can be toxic to marine life if found in large enough quantities. One estimate showed that VOCs represent less than 0.5% of total dissolved organic carbon (DOC) in seawater but have been found to represent up to 27% of the carbon in an industrialized estuary as a consequence of anthropogenic and biogenic influences (Bianchi and Varney, 1998). VOCs identified were composed of primarily alkane and aromatic hydrocarbons whose boiling points are between those of *n*-C_6 to *n*-C_{18} and heterocompounds within the same volatility range (e.g. C_1-C_4 organohalogens, aldehydes, ketones and organosulphides) (Bianchi and Varney, 1998). However, in a pair of studies conducted in the Southampton estuary by Bianchi and Varney (1998), more than 100 individual VOCs were recovered through the use of a gas-chromatograph. It should be noted however, that this region is known for extensive industrial activity compared to that of Newfoundland and Labrador.

Mass spectrometers can be used to measure VOCs as well as dissolved gases in coastal effluent plumes. Pennell (2003) used an underwater mass spectrometer to trace a simulated plume of DMS. Wenner et al. (2004) also used the underwater mass spectrometer to scan for several parameters including toluene, chloroform, benzene and DMS. A mass spectrometer determines the molecular weight of chemical compounds by separating molecular ions according to their mass-to-charge ratio (Wenner et al., 2004). The basic components of a mass spectrometer include the sample inlet, ionization source, mass analyzer, and ion detector (Pennell, 2003). Inducing either the loss or gain of a

charge generates ions that can be separated according to their mass and charge. The sample passes through a silicone membrane coupled with a quadrupole mass filter which is used for detection and quantification. Finally, the ion detector transmits a signal to a computer or data storage device where the information is stored for future analysis.

2.4 Biological Sensors

A wide range of sensors are used by scientists and biologists to determine the ecosystem conditions of the ocean. Although physical and chemical parameters can give a description of the surroundings, a biological sensor may be useful in determining ecosystem health. Biological sensors can be defined into two groups, one that measures the amount of biological activity (i.e. chlorophyll *a*) and one that uses biological processes (i.e. lipid uptake) to obtain measurements. This study will focus on the sensors using biological activity.

2.4.1 Chlorophyll *a*

There are many types of naturally occurring organic matter in the ocean. Most organic material in the ocean is termed dissolved organic matter (DOM) and is measured as DOC (Pilson, 1998). It is difficult to obtain an accurate measurement of the exact amount of organic carbon in the ocean. Some estimates have yielded figures that differ by more than a factor of two, depending on the technique utilized (Pilson, 1998). Scientists have yet to determine the structure of most organic matter in seawater, but there are several compounds that can be measured very accurately.

Seawater optical properties are useful for examining phytoplankton biomass (chlorophyll fluorescence), total suspended matter (beam attenuation or backscatter) and DOM (absorbance) (Chen, 2000). Chlorophyll *a* is the chemical used by plants to produce oxygen in the process of photosynthesis and is a common measurement in oceanography that yields a descriptive measurement of ecosystem health. The chemical is naturally found in all plants, including phytoplankton. It absorbs light in certain regions of the visible spectrum when excited by the presence of an external light source and re-emits a small portion of this light as fluorescence at longer wavelengths (WET Labs, 2004). When plants come into contact with light, chlorophyll absorbs light from different wavelengths to undergo the chemical process of converting carbon dioxide into oxygen. Therefore, the measurement of phytoplankton is critical to ensure the coastal zone is receiving adequate flushing of the effluent to give it an opportunity to refresh itself with fresh oxygen, limiting eutrophication.

The fluorescence that induces the chemical reaction involved in photosynthesis can be used to measure the amount of chlorophyll in water. Similar to fluorometers used in the detection of certain dye tracers, fluorometers can be specifically configured to measure wavelengths that would coincide with chlorophyll *a*. In general, these instruments are similar with the main difference being the range of wavelengths emitted and measured.

The chlorophyll molecule is excited at a wavelength of 460 nm and the emission generally takes place at a wavelength of 620 to 715 nm. As described in section 2.3.1, a fluorometer emits light at a predefined wavelength and measures the amount of light reflected back at another wavelength. Most commercially available *in situ* chlorophyll

fluorometers use broadband excitation and collection to enhance sensitivity to detect oceanic concentrations of chlorophyll (Desiderio et al., 1997). These sensors can be used in association with the other physical and chemical sensors to assess the overall health of the environment. In some cases, the measurement of chlorophyll is temperature sensitive and must be measured together with the parameter.

Chapter 3 Experiment Design

3.1 Source Selection

The initial thrust of this project was in the identification an effluent source (either produced or existing) that could be used to track and map a plume as it dispersed into the coastal environment. Several options were considered including the creation of an artificial plume using a submersible pump or a hose to inject enhanced freshwater into a harbour. It was determined that it would be beneficial to utilize an existing wastewater source as the data collected may also be useful to other stakeholders. Of the three types of common effluent plumes discharged in Newfoundland and Labrador, seafood processing plant effluent was identified as a potential source for the experiment once it was recognized that some important criteria could be met.

Seafood processing effluent has several physical parameters different than typical ambient conditions in Newfoundland that can be tracked including salinity, temperature and dissolved oxygen. With the addition of a dye tracer, one should be able to delineate the effluent plume as it is released into a coastal region. As discussed in Section 1.2.1, seafood processing plants discharge large amounts of potable water into the coastal environment which would provide an adequate flow rate. Also, typical seafood plants require the use of a crane for loading and offloading fishery products which would be useful for the deployment and recovery of the experimental apparatus. Finally, it was determined through discussions with Fisheries and Oceans Canada and the Department of Fisheries and Aquaculture, Government of Newfoundland and Labrador, and a literature

review, that fish plant effluents are poorly studied in the region. It was concluded that seafood processing effluent would be an optimal source to utilize in this experiment.

3.2 Study Location

Aqua-Fisheries Ltd., located in Aquaforte, Newfoundland, 47.00°N, 52.57°W was chosen as the location for the experiment. The plant is located in an inlet along the east coast of the Avalon Peninsula known as "the Southern Shore" (Figure 3.1 and 3.2). The outfall is located behind a wharf used for offloading fishery products. The plant itself is constructed on a pier that consists of a series of pilings and boards (Figure 3.3). During the production of groundfish, the outfall is located directly underneath the building. Conversely, during the production of shellfish, the waste products are discharged through an outfall 2 m above the high tide water mark. The plant processes snow crab and several groundfish species from May to October.

Figure 3.1 Island of Newfoundland
Used with permission from Laura Park, Fisheries and Oceans Canada

Figure 3.2 Aerial photograph of Aquaforte Harbour (Government of Newfoundland & Labrador, 1995)

Figure 3.3 Picture of outfall and side of fish plant

The seafloor adjacent to the plant is a gradually sloping sandy bottom (S. Fudge and Associates, 1989). At the discharge point, the depth was measured to be 2.7 m and sloped to 5 m at the end of the wharf at high tide. A map depicting water depths of Aquaforte Harbour is shown in Appendix A. The tidal range during the time of the experiment is shown in Table 3.1. There was no available data for Aquaforte Harbour; therefore the tidal range for Fermeuse Harbour located approximately 8 km south is shown.

Table 3.1 Tide Table: Fermeuse Harbour

2004-10-22 (Friday)		2004-10-26 (Tuesday)		2004-10-27 (Wednesday)	
Time	**Height (m)**	**Time**	**Height (m)**	**Time**	**Height (m)**
03:21	0.8	01:03	0.2	01:40	0.2
09:12	0.4	07:21	1.2	07:57	1.3
15:24	1.1	13:35	0.1	14:17	0.1
22:44	0.3	19:29	1.2	20:09	1.2

3.3 Equipment Selection

Although there are several sensors identified in Chapter 2 that can be used for the delineation of effluent plumes, it was determined that the following sensors would be the most applicable for this project's requirements. Selection was made in accordance to budgetary constraints, versatility and ability to use the sensors on a variety of platforms including AUVs. The platform selected for this experiment was an 18' Zeppelin inflatable boat with an electric trolling motor because no reliable AUV was available at the time of the experiment.

MicroCTD

Several parameters can be measured with a CTD that would be pertinent to any plume, especially at a seafood processing plant. Although the seafood plant was not producing

at the time of the experiment, it was determined that the difference in salinity and temperature between the coastal ocean water and the freshwater source that is typically used in the production process may yield worthwhile results.

The MicroCTD from Applied Microsystems Ltd. was selected for the experiment. It is designed to allow for integration on autonomous and remotely operated vehicles as well as independently run on a towed apparatus with the use of a battery pack and data logger (Applied Microsystems, 2004). The data logging feature is activated when the shorting plug is inserted into the instrument and it comes in contact with seawater. Conductivity, temperature and pressure comprise the main unit in the sensing system. These three parameters are used in the calculation of salinity, density and sound velocity. The sensors are activated using the software package Smart Talk™ which accompanies the instrument. Applied Microsystems Ltd. can provide integration with several types of sensors to measure chlorophyll *a*, dissolved oxygen, pH, turbidity and oxygen reduction potential (ORP). The system operates as a flow-through water sampling apparatus therefore does not require a pump to obtain samples. The MicroCTD can output single scans or a continuous data stream at a maximum scan rate of 25 Hz (Applied Microsystems, 2004). In this experiment, a sampling rate of 1 Hz was selected to ensure ease of integration with the other sensors. The MicroCTD can operate on a DC supply between 8 to 20 volts. This system was powered by a battery pack which contained three 3.6 V lithium ion batteries. The sensor package was pre-calibrated at the factory and the calibration certificate and coefficients are presented in Appendix B

Table 3.2 MicroCTD Specifications (Applied Microsystems, 2004)

Sensor	Type	Range	Accuracy	Resolution	Time Constant
Conductivity	Patented platinized 4 electrode	0-7.0 S/m	0.001 S/m	0.00015 S/m	25 ms typically
Temperature	Precision aged thermistor in beryllium copper housing	N/A	±0.005 °C	0.001 °C	100 ms
Pressure	Semi-conductor strain gauge	0 to 2, 5, 10, 20, 50, 100, 200, 400, 600, 1000 bar	±0.05 % full scale	0.1 dbar for ≥ 100 bar FS sensors	10 ms

Dissolved Oxygen

The surrounding environment of a seafood plant outfall and gurry ground are typically low in dissolved oxygen as discussed in Section 1.2.1. Therefore, it was determined that measuring the amount of dissolved oxygen in the ambient environment and within the plume would be useful for experiments concerning fish plants. The Idronaut dissolved oxygen sensor was selected to perform the experiment as it was easily integrated into the MicroCTD. Also, it has a scan rate of 1 Hz with a range of 0 to 15 mg/L and an accuracy of 0.2 mg/L. This model is a polarographic sensor which reports its measurements in percent saturation.

The dissolved oxygen sensor required calibration prior to its use. This task was performed by connecting the sensor to a computer and placing it in oxygen depleted solution of sodium sulphate ($NaSO_3$) solution and recording the initial DO raw data value known as the zero oxygen count. Next, the sensor was removed from the solution, rinsed

with fresh water and allowed to stabilize in air at room temperature at which point the DO is recorded. The zero oxygen count is entered into the calibration window and the Smart Talk™ software uses the two values to calculate the air saturation point. The calibrated sensor is then considered operational.

Fluorometer

A dye tracer was selected to ensure that the plume could be detected to low levels and could be differentiated from ambient conditions. The fluorometer selected for this study was calibrated to detect rhodamine WT (RWT) to 0.04 ppb. The Cyclops-7 fluorometer from Turner Designs specifications are outlined in Table 3.2. This instrument was also pre-calibrated prior to shipment. Its calibration certificate is shown in Appendix B.

Table 3.3 Cyclops-7 Specifications (Turner Designs, 2004)

Parameter	**Specifications**
Minimum detection limit	0.04 ppb RWT
Dynamic range (based on gain setting)	×1: 0 - 1 000 ppb, RWT ×10: 0 - 100 ppb, RWT ×100: 0 - 10 ppb, RWT
Power draw	@3V: Max 360 mW ≥5V: Max 265 mW
Input Voltage	3 – 15 VDC
Signal Output	0 – 5 VDC
Temperature Range	Ambient: 0 to 50 °C Water Temp: -2 to +50°C
Light Source	Light emitting diode
Excitation wavelength	RWT 550 nm
Emission wavelength	590 – 715 nm
Detector	Photodiode
Detection Wavelength	300 – 1,100 nm
Warm up time	5 seconds
Dimensions (excluding connector)	Length: 10.9 cm Diameter: 2.22 cm
Weight	160 g
Depth Rating	600 m

Sensor apparatus

Consideration of sensor placement was necessary to ensure that the sensors would cause the least disturbance of the plume and not skew the results. The back board of the Zeppelin boat was measured to be 0.53 m; therefore, the apparatus was required to be mounted below this point. The sensors and battery pack were mounted onto a piece of plywood using their mounting brackets. The plywood was then mounted onto the base of a 2" × 4" × 8' piece of wood with 1'of clearance to ensure safety of the sensor package. The board was mounted onto the back of the boat using two C-clamps so that the sensors were facing in the direction of flow. The board was mounted next to the electric trolling motor that was used to navigate the study area. It produced some dispersion of the dye and waste water but much less than the amount that would have been produced if a gas-powered outboard motor was utilized. Figure 3.4 shows the sensors mounted onto the board while Figure 3.5 depicts the entire apparatus mounted to the boat with C-clamps.

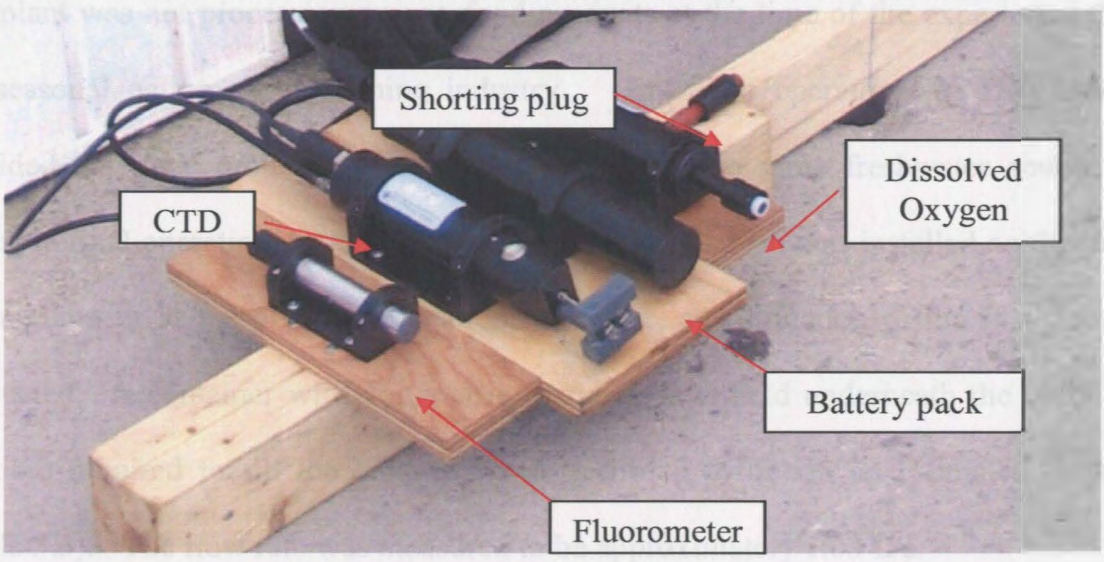

Figure 3.4 Sensors mounted to plywood prior to deployment

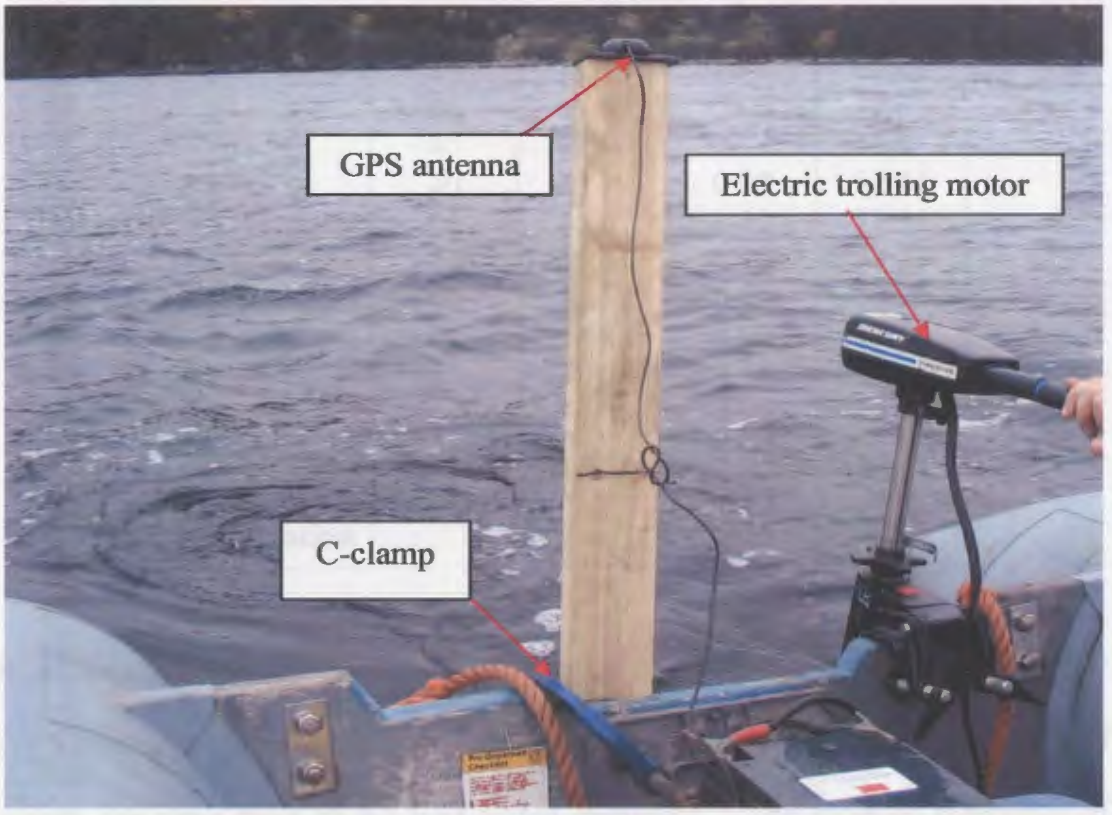

Figure 3.5 Sensor apparatus mounted on boat with GPS antenna

3.4 Experiment Apparatus

The plant was not processing any seafood products at the time of the experiment due to the seasonal nature of the fishing industry. The plant operator, Mr. Don Graham, provided a typical production level flow rate from the same freshwater source used during normal operations. No gauge or metering mechanism was installed on the plant's water pump or at the discharge location; therefore, an estimation of the flow rate was conducted. A container with volumetric markings was held underneath the outfall and the time required to fill the container was recorded to obtain an estimated flow rate (Table 3.3). The flow rate was measured to be approximately 1.03 L/s.

Table 3.4 Determination of typical plant flow rate

Trial	L	sec	L/sec	L/min
1	40	35.50	1.13	67.61
2	40	41.69	0.96	57.57
3	40	54.00	0.74	44.44
4	40	45.79	0.87	52.41
5	60	46.07	1.30	78.14
6	60	50.54	1.19	71.23
7	40	42.30	0.95	56.74
8	60	54.88	1.09	65.60
9	40	39.28	1.02	61.10
10	60	55.20	1.09	65.22
Average	**48**	**46.53**	**1.03**	**62.01**
Standard deviation			**0.16**	**9.71**

The proposed experimental procedure involved using a pump to inject the dye into the water at a constant rate of 2 L/min. However, due to pump failure at the launch of the experiment, the same ratio of dye was added manually. The supplier directions of the rhodamine WT indicate that by using one tablet in 60 gallons of water, a concentration ratio of 1 ppm is obtained. Following the method utilized by Pennell (2003), an estimation of the initial mixing was conducted using a CORMIX simulation. A concentration of 500 ppb was determined to be ample given the fluorometer detection limits of 0.04 ppb.

In order to adequately mix the dye, a concentrated mixture of freshwater and the dye tablets was added to the overall flow inside the plant. It was required to travel 5 m then drop 2 m (at high tide) into a catch basin (i.e. a fish box) before being discharged through a 2" PVC submerged pipe (Figure 3.6). The fish box had an overflow pipe and a 2" opening at its base was placed underneath the outfall. A gate valve was attached to the

box at the 2" opening to maintain a constant head within the fish box thereby ensuring a constant pressure and flow rate. The fish box had a storage capacity of 793 L to the top of the overflow pipe and 1,321 L to the top of the box. The estimated weight of the box with water was 1,205 kg. Floating dock modules (capacity of supporting 94 kg each), supplied by the National Research Council of Canada's Institute of Ocean Technology, were utilized as a platform to hold the catch basin apparatus. Thirty modules were fastened together then onto the side of the building/pier to support the weight of the fish box with water and personnel.

Since there are no standardized piping configurations for liquid fish plant effluent, it was determined that the outfall should be submerged to coincide with the prediction model CORMIX1 which was used in the prediction models for submerged outfalls (Jirka et al., 1996). To submerge the outfall, two sections of 2" PVC pipe with two elbow pieces were attached to the gate valve in the configuration show in Figure 3.6. This configuration yielded an outfall depth of 1.1 m from the surface.

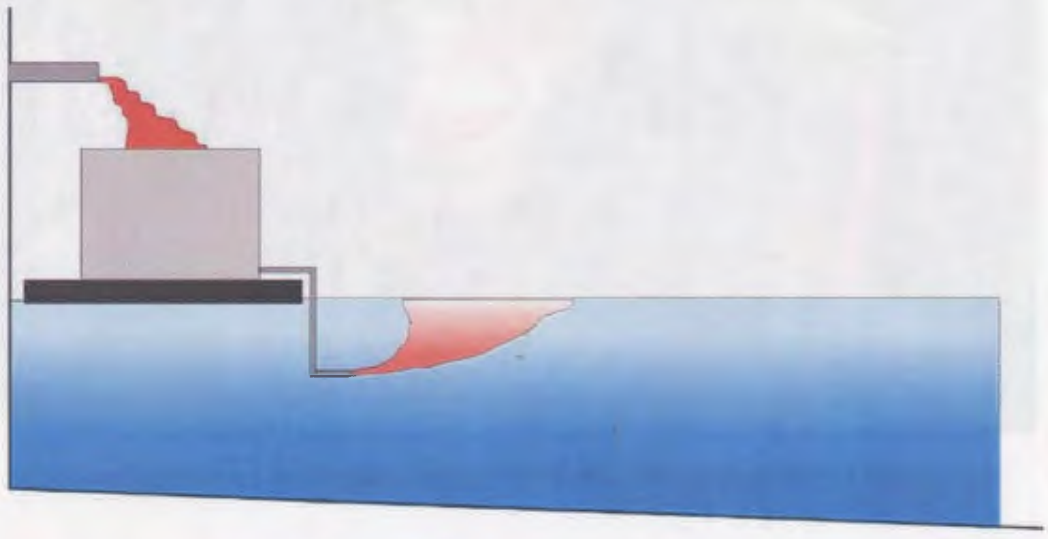

Figure 3.6 Experimental apparatus

3.5 Experimental Method

For each trial, all team members were briefed and assigned tasks. One individual was responsible for dye injection (Figure 3.7). Another team member was required to ensure the catch basin apparatus was operating efficiently, i.e. the box was centered under the outfall pipe, the incoming flow rate was the same as the outgoing flow rate and the submerged pipe was directed straight down as intended (Figure 3.8). Another person was required to drive the Zeppelin (Figure 3.9) in a "lawnmower" pattern (Figure 3.10) for each cast and adjust the height of the sensor board. This pattern was selected to ensure that there would be adequate coverage throughout the harbour and not solely focused on the region immediately adjacent to the outfall.

Figure 3.7 Mixing of rhodamine WT into the outfall pipe

Figure 3.8 Fish box full of mixed simulated effluent

Figure 3.9 Performing the experiment with sensors fastened to the boat

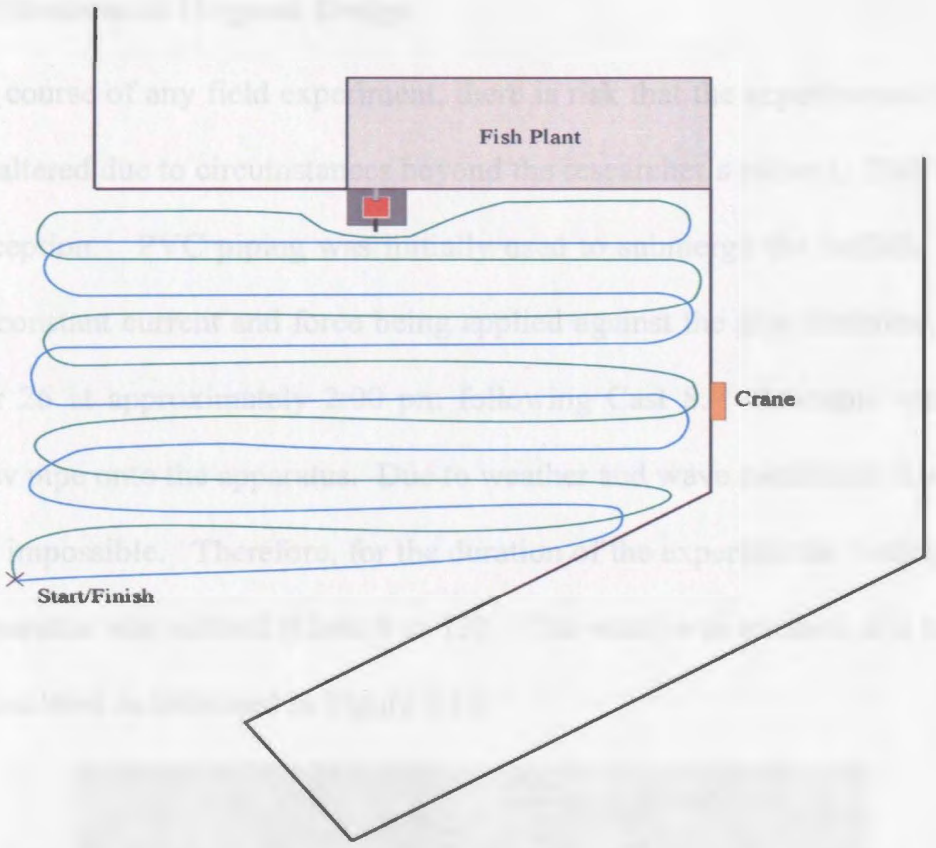

Figure 3.10 Lawnmower pattern and general experiment layout

The sensor suite was activated for data logging using a laptop computer and the shorting plug. Next, the GPS unit was set to collect the time and location every second into a text file on the laptop computer through a USB port. The GPS antenna was mounted onto a piece of stainless steel fixed to the top of the sensor apparatus. The sensor suite was lowered into the water. The boat traveled at an average speed of 1.7 km/hr. Following the end of each cast, the sensors were lifted out of the water to ensure adequate data separation for data management purposes. Three to five casts were conducted which correspond to each depth sampled during each trial.

3.6 Modifications to Original Design

During the course of any field experiment, there is risk that the experimental design will need to be altered due to circumstances beyond the researcher's control. This experiment was no exception. PVC piping was initially used to submerge the outfall. However, due to the constant current and force being applied against the pipe structure, it snapped on October 26 at approximately 2:00 pm following Cast 8. Attempts were made to attach a new pipe onto the apparatus. Due to weather and wave conditions it was deemed logistically impossible. Therefore, for the duration of the experimental testing procedure no pipe apparatus was utilized (Casts 9 to 13). The water was released at a height of 50 cm above sea level as indicated in Figure 3.11.

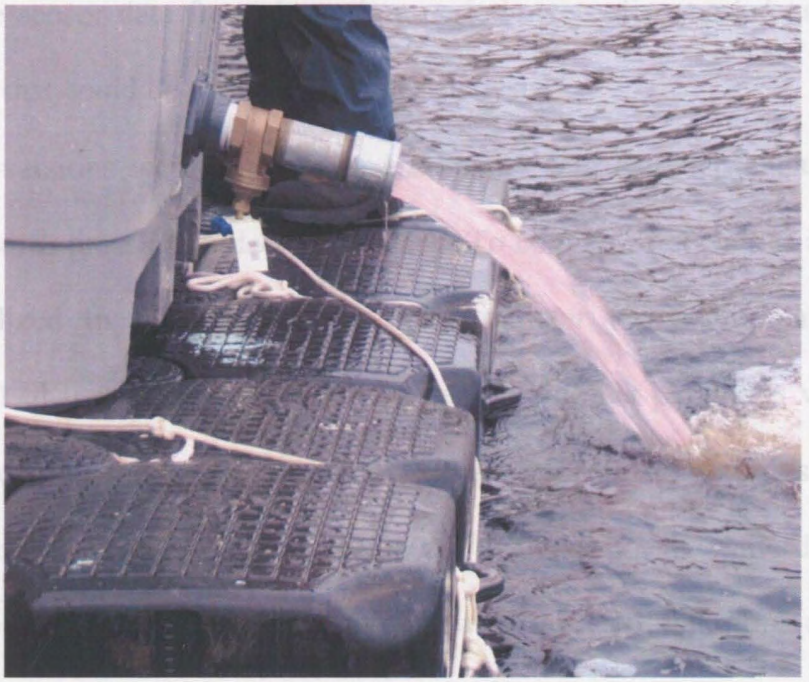

Figure 3.11 Fish box with no pipe

Chapter 4 Results

4.1 Data Analysis

All sampled data from the sensors is stored within the data-logger component of the MicroCTD as an ACSII file for each cast recognized by the unit. Following the end of each session, the data was downloaded from the sensors to a laptop computer using the Smart Talk™ software and saved into a .csv (Comma Separated Value) file. This data type is easily converted into a Microsoft Excel™ spreadsheet. Along with the sensor data, the MicroCTD records the date and time of all measurements collected. This information was used to match the spatial location from the GPS unit to the sensor data. There were several instances where the GPS lost its reception and only recorded the time component. The sensor data from these time periods were disregarded as there was no spatial reference that could be useful for further analysis.

Several unit conversions were required to ensure the data was in standard units. The MicroCTD measures pressure in decibars (dbar). To convert these values into a measure that can be utilized in further analysis, the parameter was manipulated using the following ratio: 1 dbar = 1.01998 m (metre of head). Another parameter which required some manipulation was rhodamine WT (RWT). The fluorometer output is given in volts as it measures the fluorescence signal of RWT. Converting this value depends on the gain setting of the fluorometer which in this case was Gain ×10; therefore, all fluorometer data was multiplied by a factor of 10 to provide the measurements in parts per billion (ppb) by volume.

The sensor apparatus was lifted out of the water at the end of each run to provide adequate data separation between each cast. These were at approximately 20 minute intervals. The values of the pressure and other parameters changed considerably. These extreme values were disregarded by eliminating samples within the range: -1.0 m < depth < 0.15 m. Following the data filtering procedures, a total of 17,110 data points with their temporal and geographical signatures were used for further analysis. The data was separated into four trials representing the different sessions of the experiment as seen in Table 4.1. Within each trial, there are several depths being represented. For example, during Trial 1, 5 casts were completed at 1.00, 0.41, 0.67, 0.98 and 1.12 m over a three hour period.

Table 4.1 Data organization

Trial Number	Date and Time	Casts	Data Points
Trial 1	October 22, afternoon	1 - 5	5145
Trial 2	October 26, morning	6 - 8	5652
Trial 3	October 26, afternoon	9 - 12	5216
Trial 4	October 27, morning	13	1097

The data was imported into a Microsoft Access™ database and then converted to an ArcView™ 8.3 geodatabase. Initially, the data was entered into the geodatabase as a series of point features with attributes corresponding to each of the measured parameters. All data was contained in one file for all the data points. This file had to be separated into the individual trials by selecting each cast corresponding to the specific trial and saving them into four distinct shapefiles. This step was essential to perform any analysis on the data as each shapefile represents the source data on which to base future calculations.

Interpolation by inverse distance weighted (IDW) averaging was used to obtain a raster image with a grid resolution of 0.5 m to ensure that the coverage of the data was not patchy or dispersed. IDW is a well-known interpolation method for creating continuous surfaces (Kitsiou and Karydis, 2001). This method is used to estimate cell values of a specific attribute (z) by taking the average of the values of sample data points in the vicinity of each cell of the newly formed grid. A search radius is used to identify data in the vicinity of the new grid node. Points that are closest to the center of a cell are estimated to have a stronger influence than points at the extremities dependant on the power (p) of the weighting function. The distance from the grid node is used to give a weight to the point. The method presumes that the variable being mapped decreases in influence with distance from its sampled location (ERSI, 2005). The method is calculated using the following set of equations:

$$\hat{z}(x) = \sum_{i=1}^{n} \lambda_i \cdot z(x) \qquad [3]$$

where λ_i is given by the weighting function:

$$\sum_{i=1}^{n} \lambda_i = 1 \qquad [4]$$

and can also be expressed as d^{-p} so that the entire weighting function can be written as

$$\hat{z}(x) = \frac{\sum_{i=1}^{n} z(x_i) \cdot d_{ij}^{-p}}{\sum_{i=1}^{n} d_{ij}^{-p}} \qquad [5]$$

The interpolated values of any point within the data set are bounded by $\min(z_i) \leq \hat{z}(x) \leq \max(z_i)$ so that $\lambda_i > 0$ (Kitsou and Karydis, 2001). This step was

completed for each trial's parameters of interest (temperature, salinity, dissolved oxygen and rhodamine WT). The result of this function is a grid where each cell within the study area represents a distinct value and continuous surface for each parameter. The grid represents a horizontal profile of each trial for each parameter that was used to determine trends in the data.

4.2 Trial 1 – October 22, 2004

Five casts were obtained during the afternoon of October 22 at an average depth of 0.84 m with an average seawater density of 1020.1 kg/m^3 and ambient temperature of 9.6°C. Wind speed was 20 km/hr.

The raw data for all casts in this trial are plotted in Figure 4.1 against the same time scale. The trends observed for temperature and salinity are correlated as expected. Both parameters are constant then decrease at the start of Cast 2. Following a 20-minute interval, values increase and begin to level near the end of the trial. The dissolved oxygen (DO) measurements are also constant with an increasing region at the same point at which the salinity and temperature decrease. As the trial continues, the DO values begin to decline consistent with the other parameters. All DO measurements show that all regions of the study area are supersaturated. With respect to RWT, at the start of the trial there are several large peaks observed in the RWT data and several more spikes approximately one hour later during Cast 4.

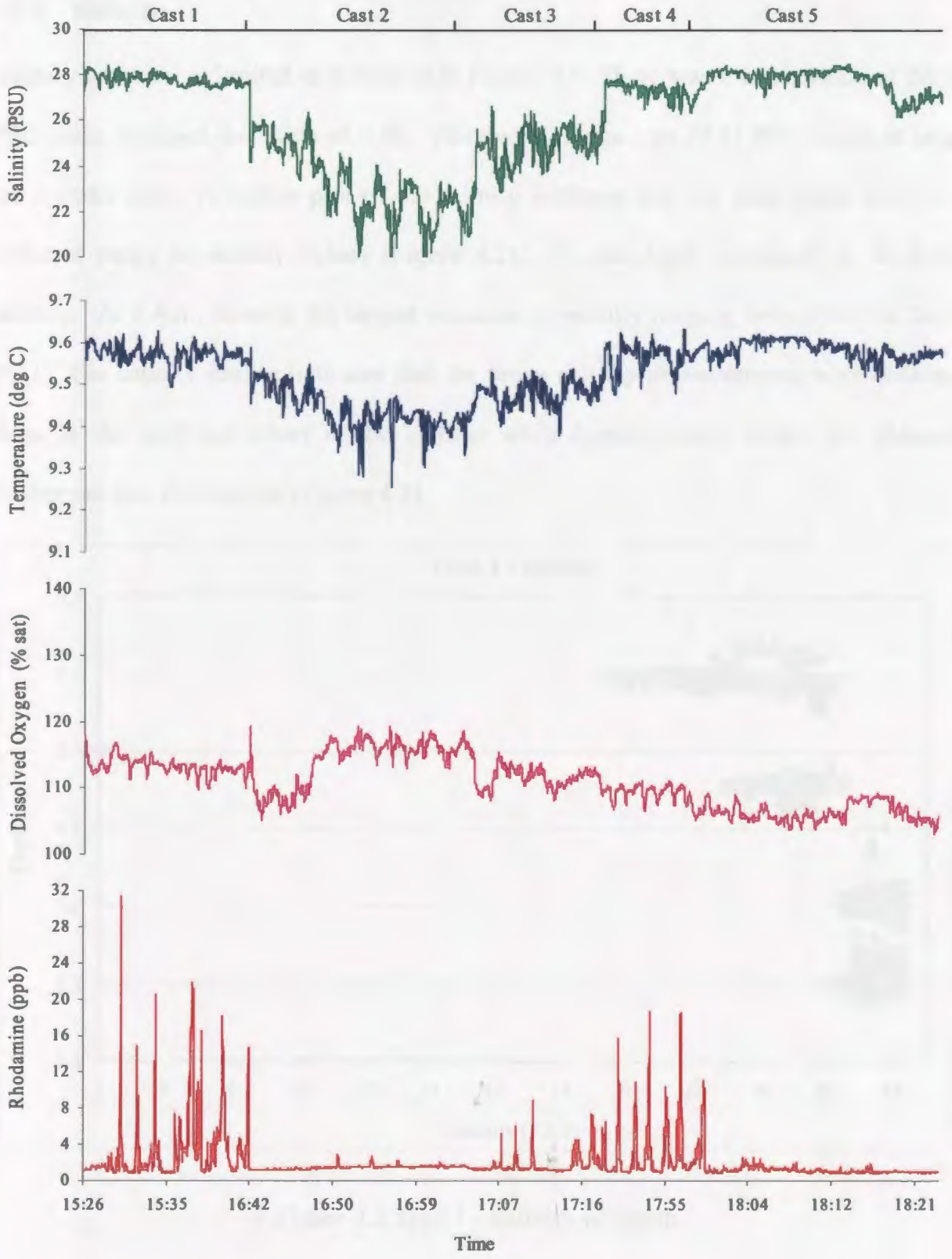

Figure 4.1 Trial 1 - All parameters vs time

4.2.1 Salinity

Salinity variation is limited as indicated in Figure 4.1. There was a mean value of 26.07 PSU and a standard deviation of 2.18. The overall range was 10.31 PSU which is large for a small area. A scatter plot of the salinity indicates that for each depth there is a different range of salinity values (Figure 4.2). As the depth increases, so does the salinity. At 0.4 m, there is the largest variation in salinity ranging from 19.21 to 26.67 PSU. The salinity profile indicates that the lower salinity measurements were obtained close to the wall and wharf in the harbour while higher salinity values are obtained further out into the harbour (Figure 4.3).

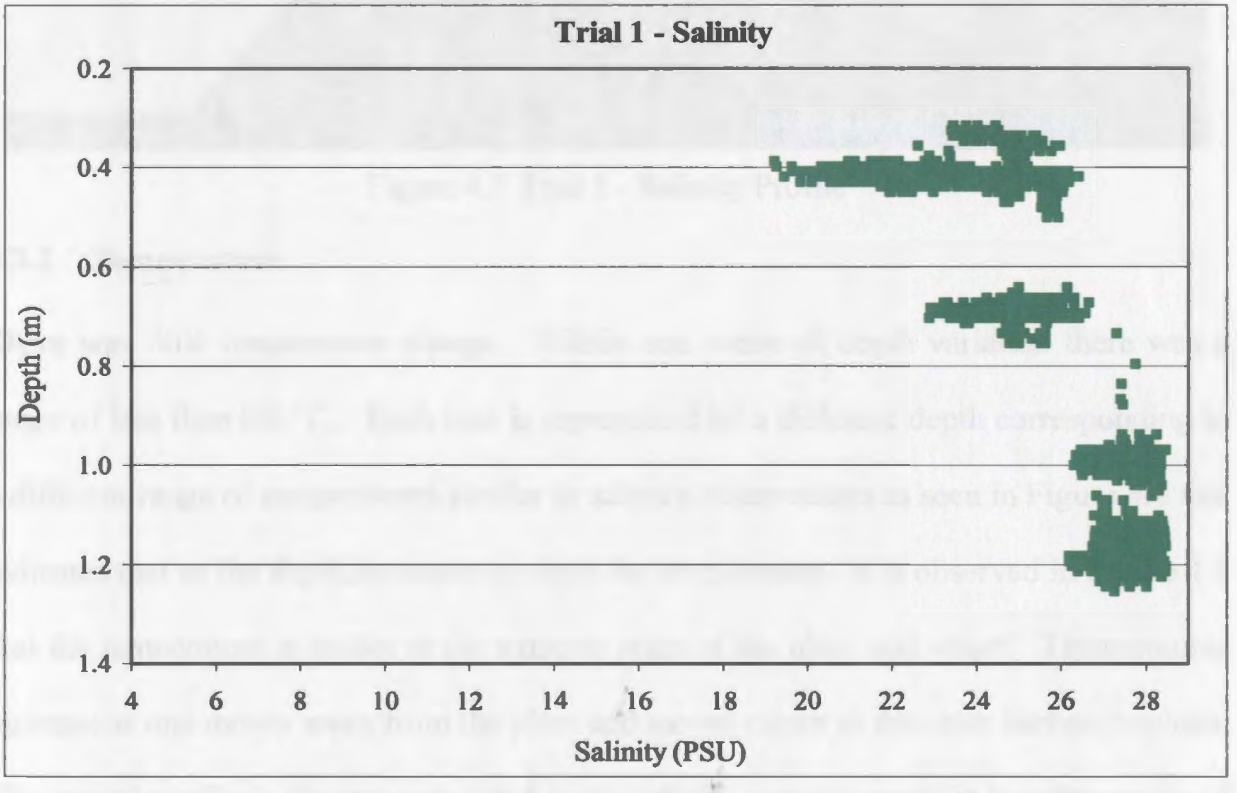

Figure 4.2 Trial 1 - Salinity vs Depth

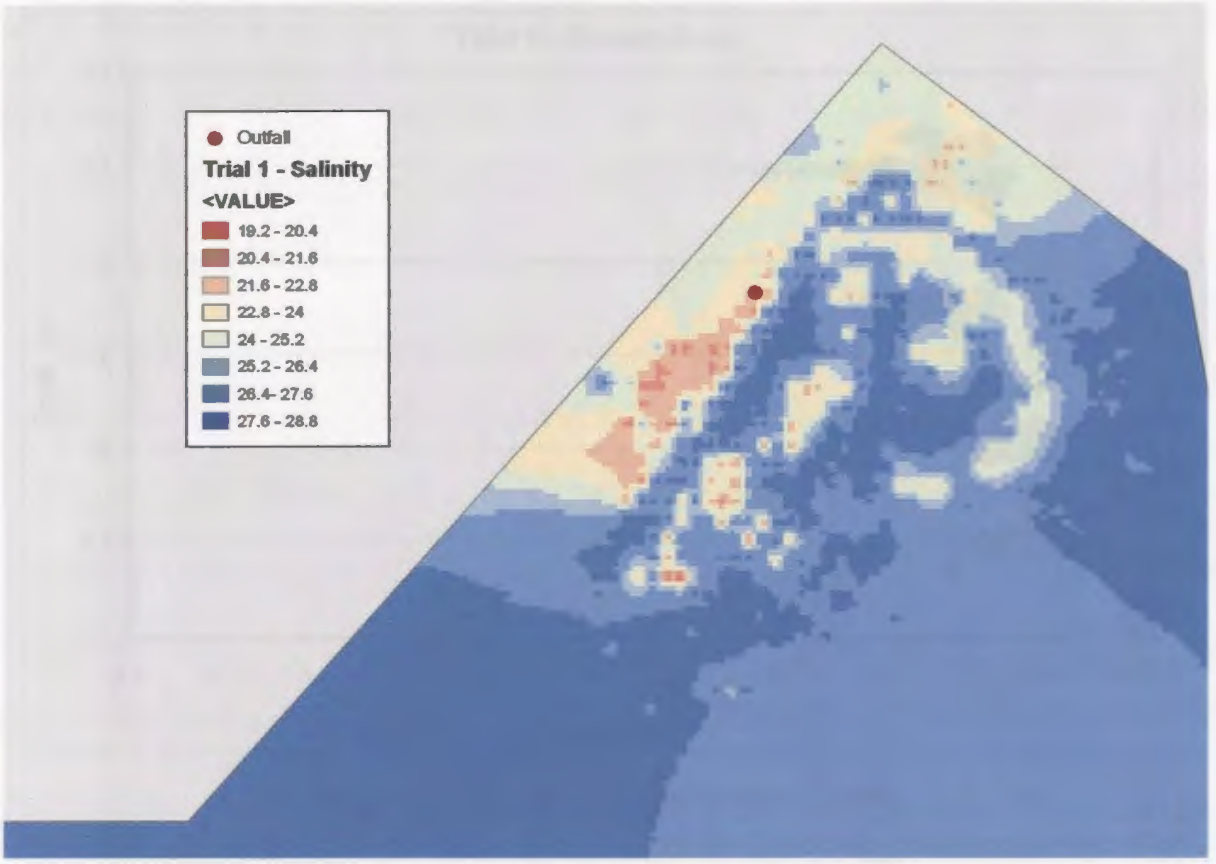

Figure 4.3 Trial 1 - Salinity Profile

4.2.2 Temperature

There was little temperature change. Within one metre of depth variation there was a range of less than 0.5 °C. Each cast is represented by a different depth corresponding to a different range of temperatures similar to salinity observations as seen in Figure 4.4 that indicates that as the depth increases so does the temperature. It is observed in Figure 4.5 that the temperature is colder at the extreme edge of the plant and wharf. Temperatures increase as one moves away from the plant and moves closer to the outer harbour regions. The spatial profile is directly correlated to the salinity measurements in that the region of low temperature next to the building is identical to that of the low salinity region.

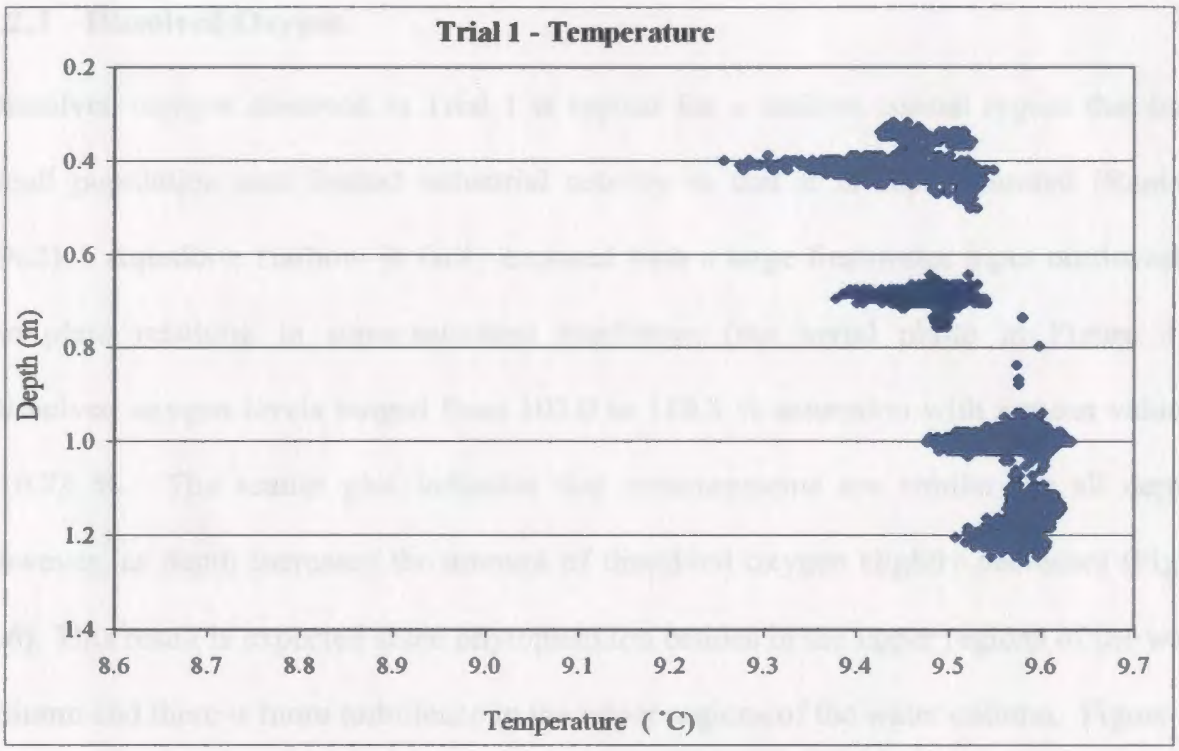

Figure 4.4 Trial 1 - Temperature vs Depth

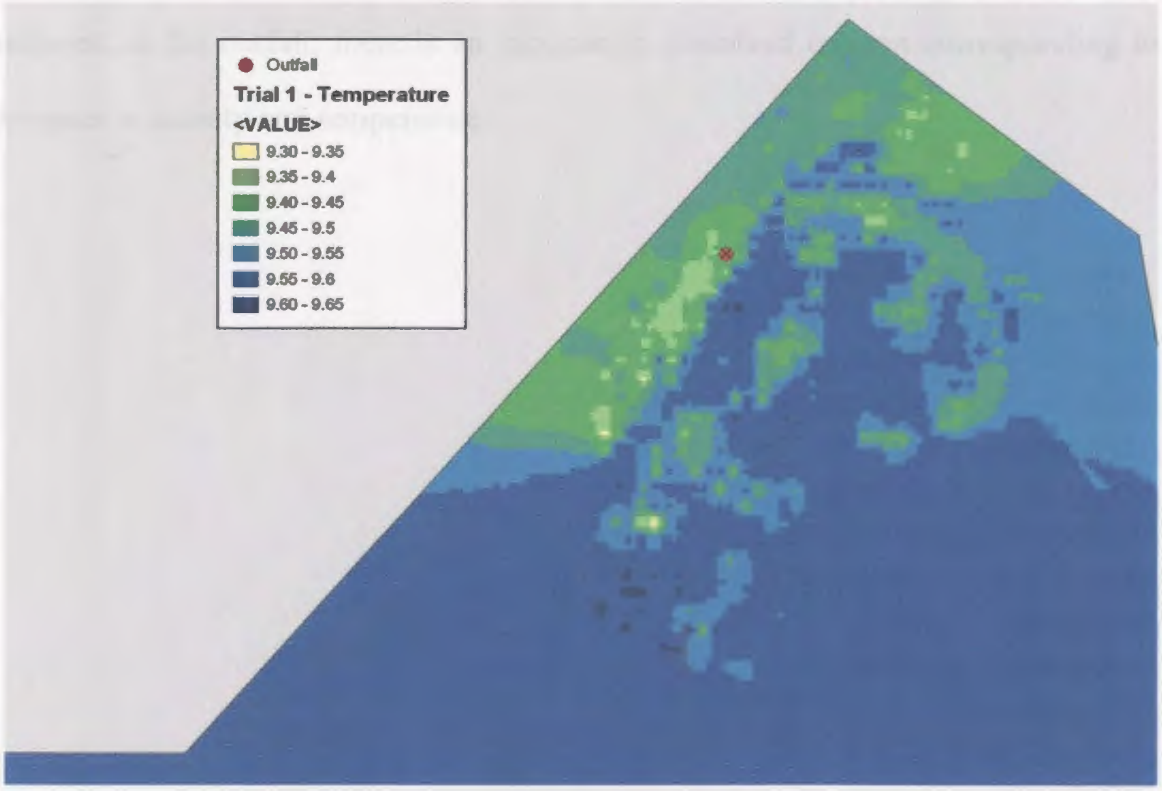

Figure 4.5 Trial 1 - Temperature Profile

4.2.3 Dissolved Oxygen

Dissolved oxygen observed in Trial 1 is typical for a shallow coastal region that has a small population and limited industrial activity in that it is supersaturated (Ramsey, 1962). Aquaforte Harbour is fairly exposed with a large freshwater input northwest of the plant resulting in super-saturated conditions (see aerial photo in Figure 3.2). Dissolved oxygen levels ranged from 103.0 to 119.3 % saturation with a mean value of 110.75 %. The scatter plot indicates that measurements are similar for all depths; however, as depth increases the amount of dissolved oxygen slightly decreases (Figure 4.6). This result is expected since phytoplankton resides in the upper regions of the water column and there is more turbulence in the upper regions of the water column. Figure 4.7 indicates the trend of the dissolved oxygen saturation is related to the other parameters: southwest of the outfall, there is an increase in dissolved oxygen corresponding to the decreases in salinity and temperature.

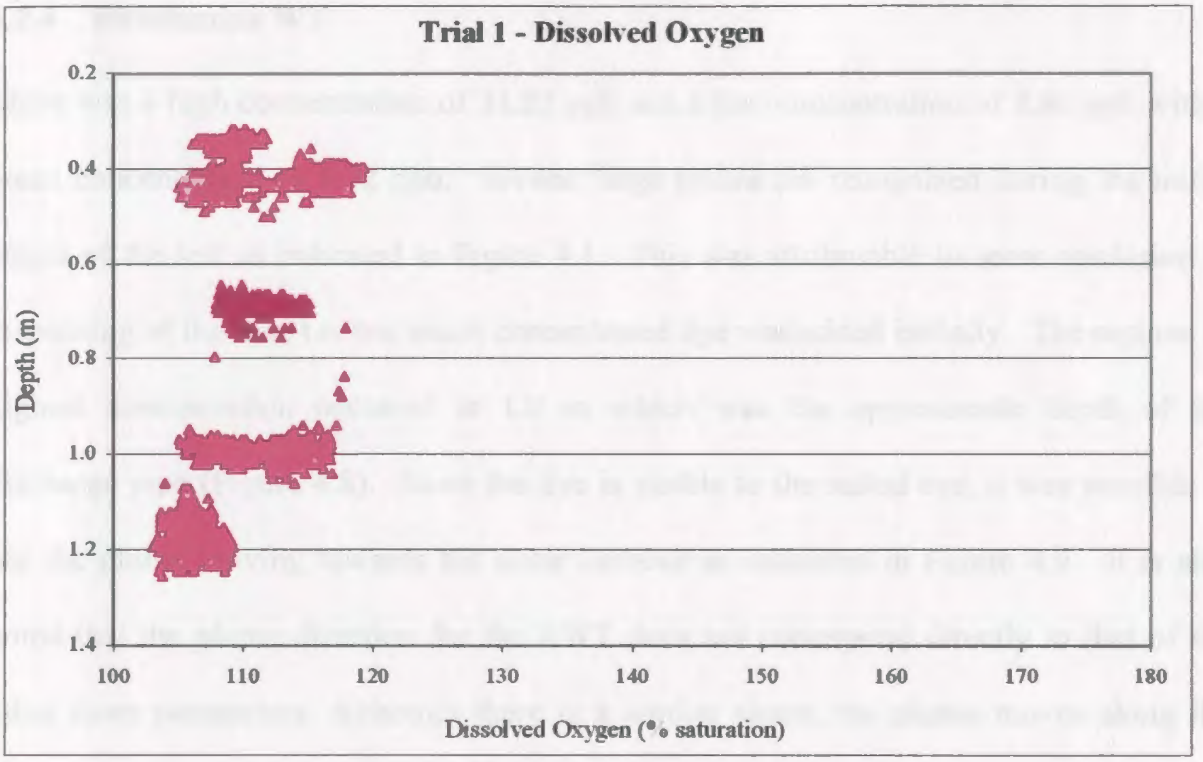

Figure 4.6 Trial 1 - Dissolved Oxygen vs Depth

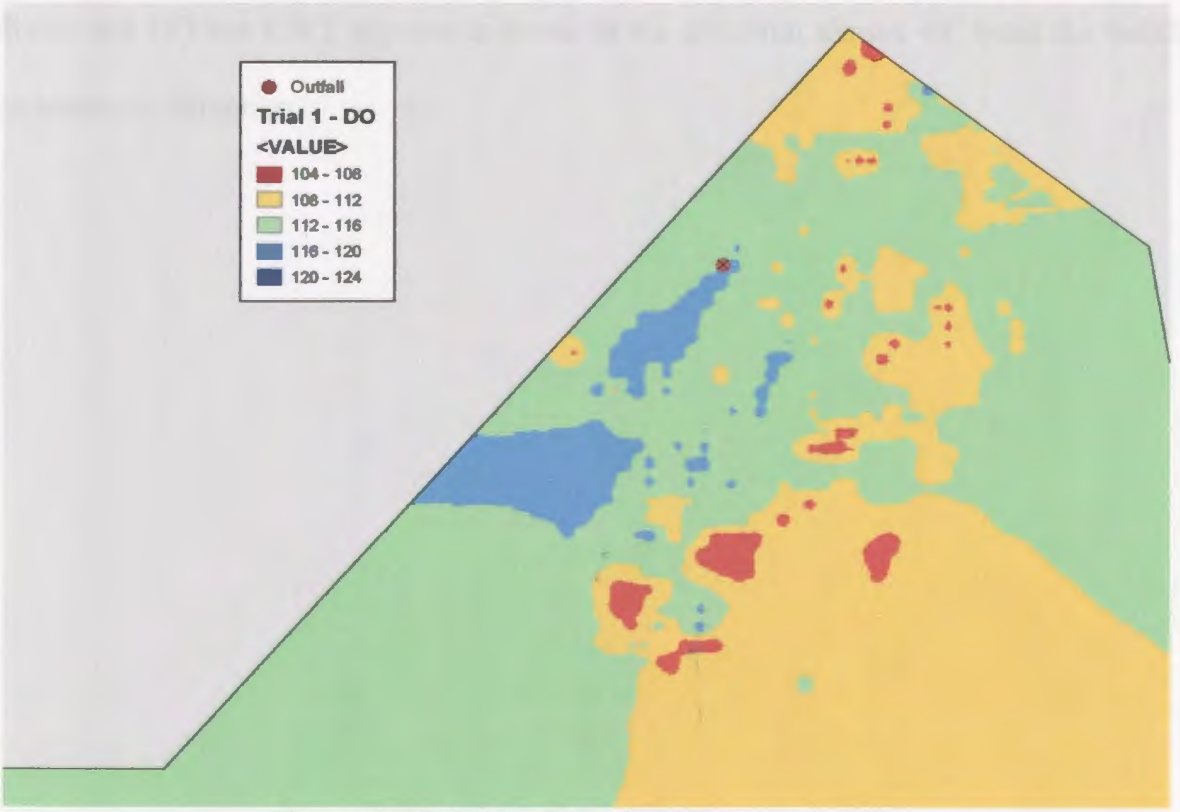

Figure 4.7 Trial 1 - Dissolved Oxygen Profile

4.2.4 Rhodamine WT

There was a high concentration of 31.27 ppb and a low concentration of 0.80 ppb with a mean concentration of 1.92 ppb. Several large spikes are recognized during the initial stages of the test as indicated in Figure 4.1. This was attributable to some confusion in dispensing of the dye, i.e. too much concentrated dye was added initially. The regions of highest concentration occurred at 1.0 m which was the approximate depth of the discharge pipe (Figure 4.8). Since the dye is visible to the naked eye, it was possible to see the plume moving towards the outer harbour as indicated in Figure 4.9. It is also noted that the plume direction for the RWT does not correspond directly to that of the other three parameters. Although there is a similar shape, the plume moves along the building and straight out to the harbour in a south-westerly direction for temperature, salinity and DO but RWT appears to travel in the direction almost 45° from the building in a southerly direction.

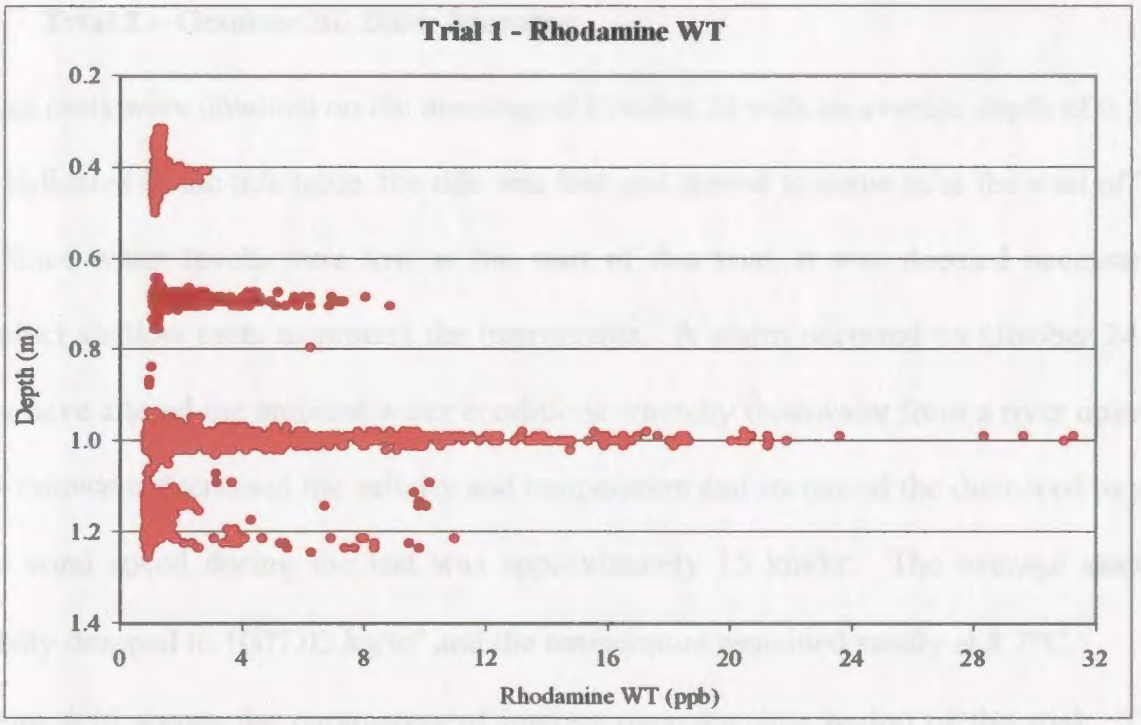

Figure 4.8 Trial 1 - RWT vs Depth

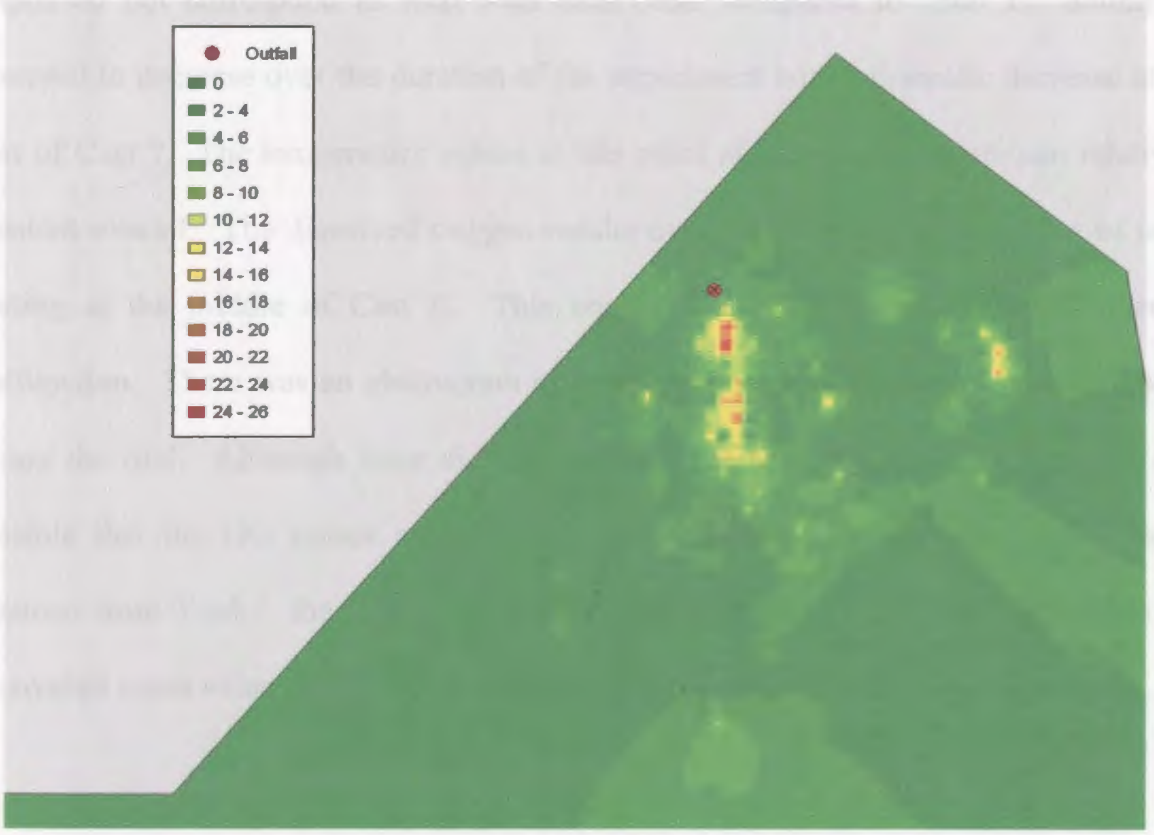

Figure 4.9 Trial 1 - RWT Profile

4.3 Trial 2 – October 26, 2004: Morning

Three casts were obtained on the morning of October 26 with an average depth of 0.47 m. As indicated in the tide table, the tide was low and started to come in at the start of Trial 2. Since water levels were low at the start of this trial, it was deemed necessary to conduct shallow casts to protect the instruments. A storm occurred on October 24 that may have altered the ambient water conditions whereby freshwater from a river upstream and rainwater decreased the salinity and temperature and increased the dissolved oxygen. The wind speed during the test was approximately 15 km/hr. The average seawater density dropped to 1007.03 kg/m^3 and the temperature remained steady at 8.7°C.

Figure 4.10 shows the parameters of interest over the time period of the trial. These graphs do not correspond as well with each other compared to Trial 1. Salinity is observed to decrease over the duration of the experiment with a dramatic decrease at the start of Cast 7. The temperature values at this point also decrease but remain relatively constant overall. The dissolved oxygen results over time appear to have a lot of noise starting at the middle of Cast 6. This could be a result of sensor interference or malfunction. There was an obstruction near the southwest wall that the sensor stick hit during the trial. Although there did not appear to be any damage to the sensors, it is possible that the DO sensor could have been affected. Comparable to the results obtained from Trial 1, the initial cast has the highest spikes in RWT measurements but the overall mean value of RWT concentration is much lower.

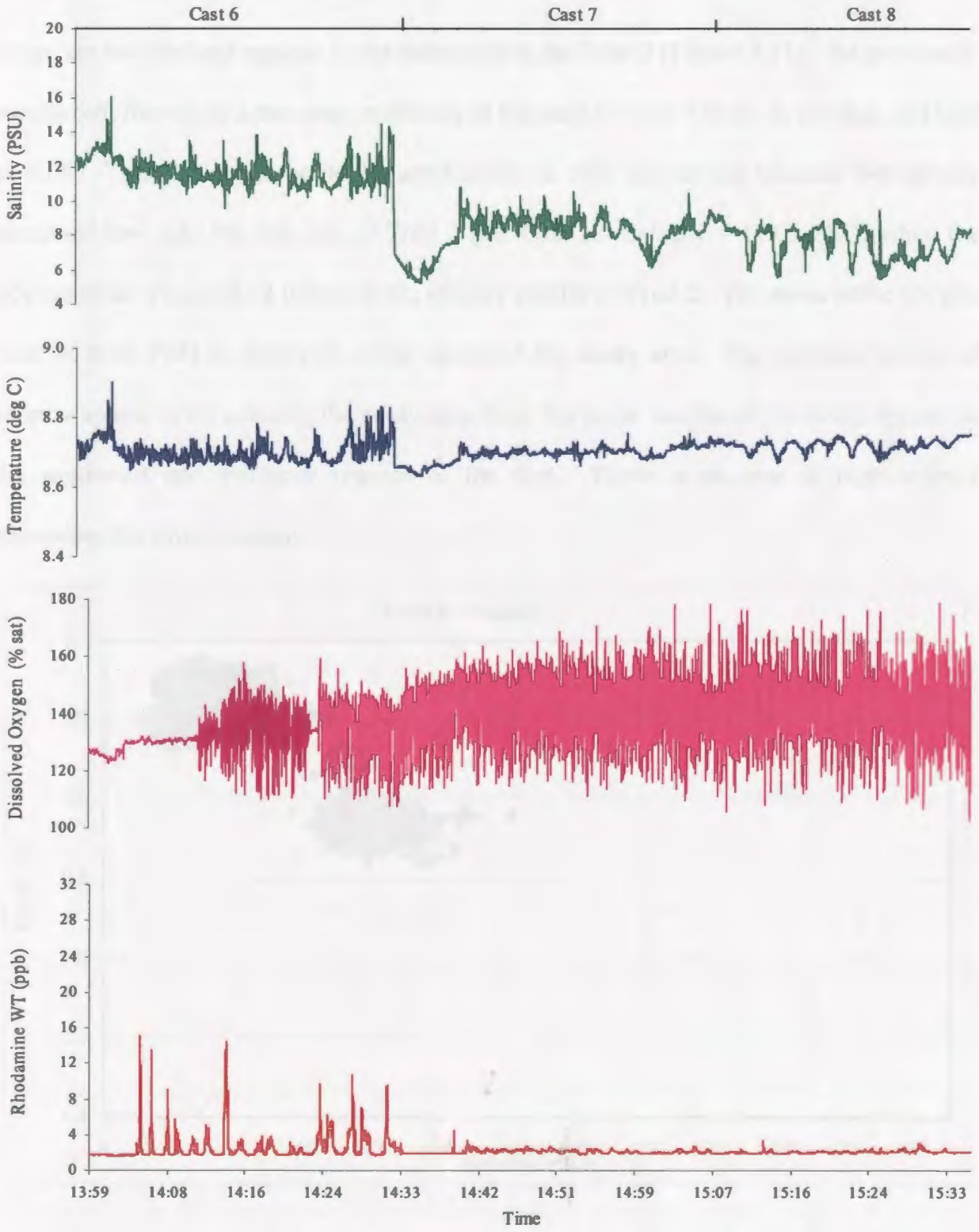

Figure 4.10 Trial 2 - All data vs time

4.3.1 Salinity

There are two defined regions in the salinity data for Trial 2 (Figure 4.11). As previously mentioned, there was a decrease in salinity at the start of Cast 7 from an average of 11.24 to 8.08. This difference could be attributable to tidal movement because the salinity remained low until the last cast of Trial 3 (i.e. Cast 12: Salinity = 11.09 PSU) when the tide came in. Figure 4.12 indicates the salinity profile of Trial 2. The mean value for this Trial of 9.23 PSU is observed at the center of the study area. The extreme values of salinity appear to be entering the study area from the outer reaches of the study region, in the southwest and southeast regions of the plot. There is an area of high salinity separating the lower regions.

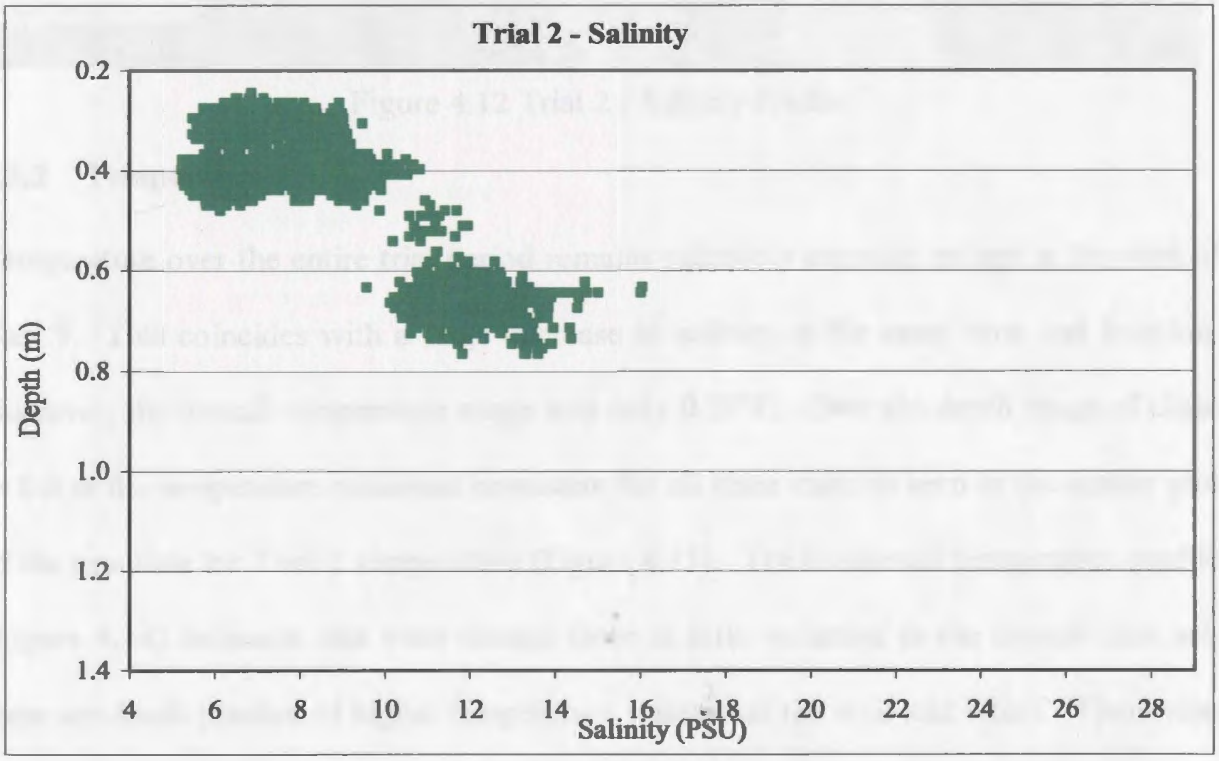

Figure 4.11 Trial 2 - Salinity vs Depth

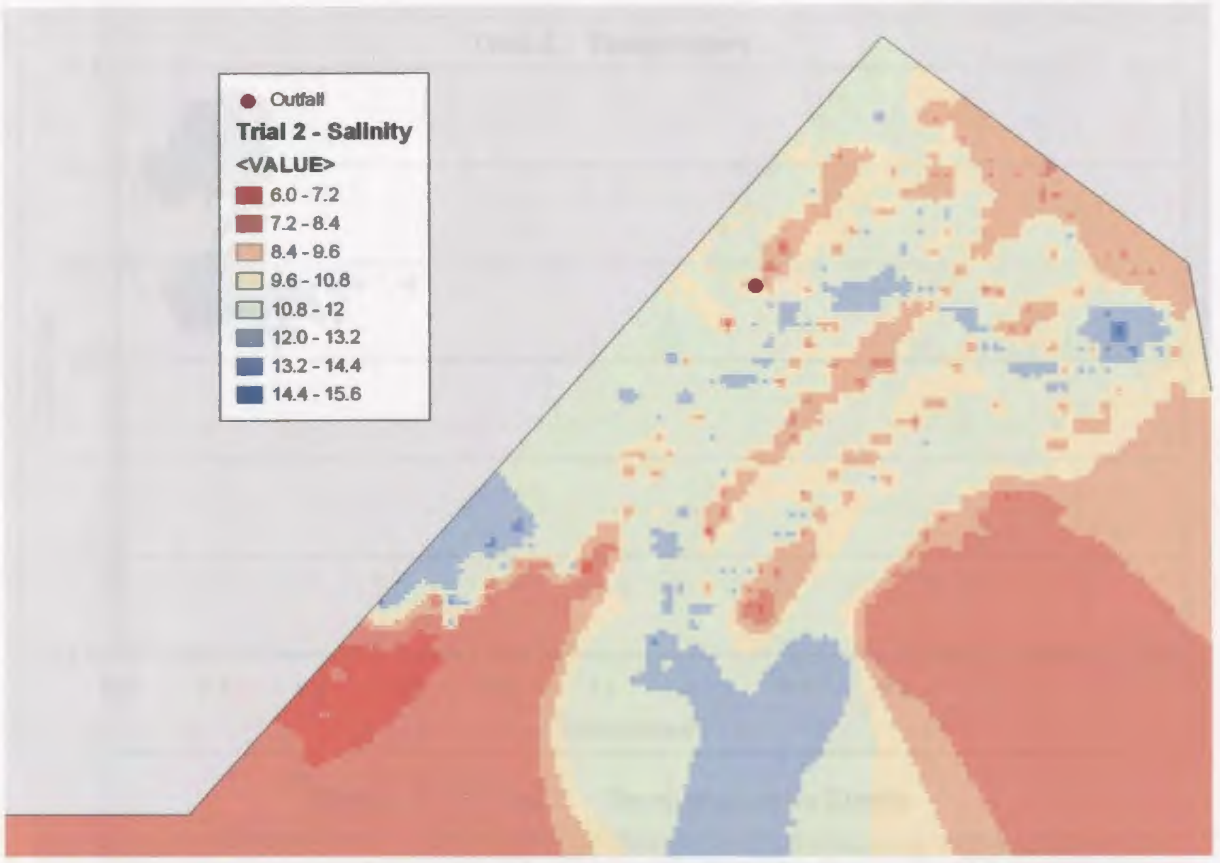

Figure 4.12 Trial 2 - Salinity Profile

4.3.2 Temperature

Temperature over the entire trial period remains relatively constant except at the start of Cast 7. This coincides with a large decrease in salinity at the same time and location. However, the overall temperature range was only 0.27°C. Over the depth range of close to 0.6 m the temperature remained consistent for all three casts as seen in the scatter plot of the raw data for Trial 2 temperature (Figure 4.13). The horizontal temperature profile (Figure 4.14) indicates that even though there is little variation in the overall data set, there are small patches of higher temperature water near the wall and wharf. There also appears to be an influx of cooler water entering the study area from the inner reaches of the harbour from the lower left hand corner of the plot in a south-westerly direction.

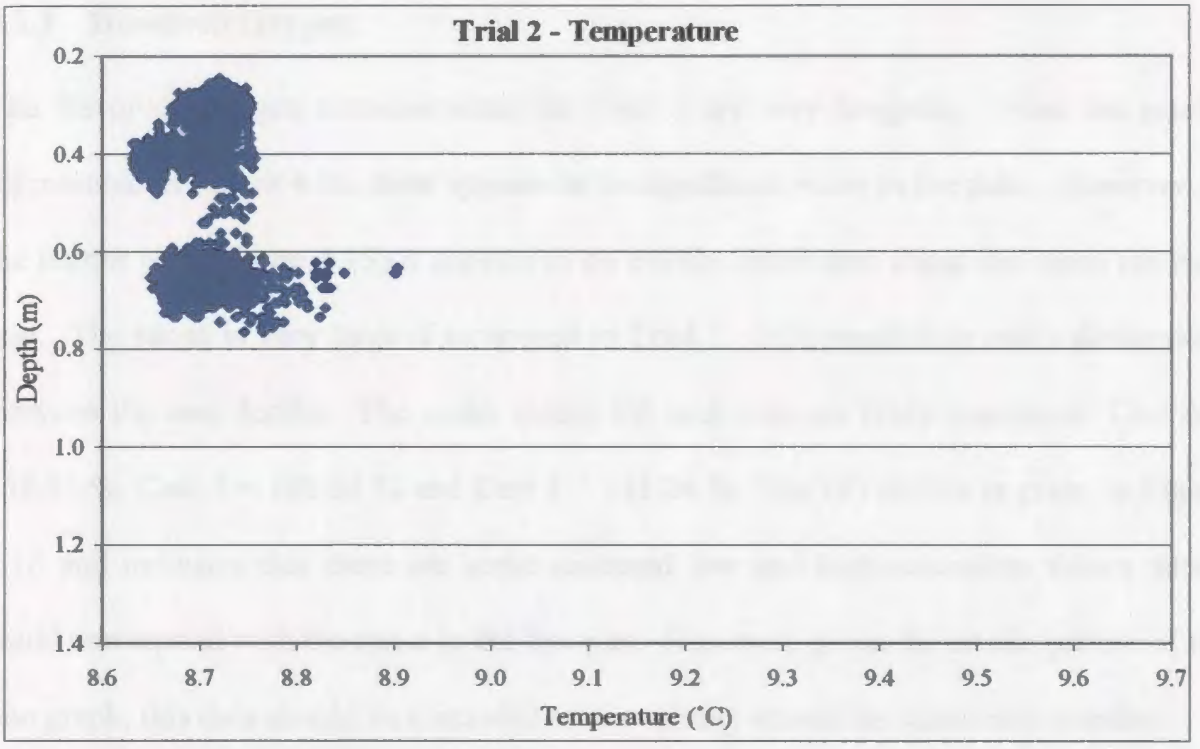

Figure 4.13 Trial 2 - Temperature vs Depth

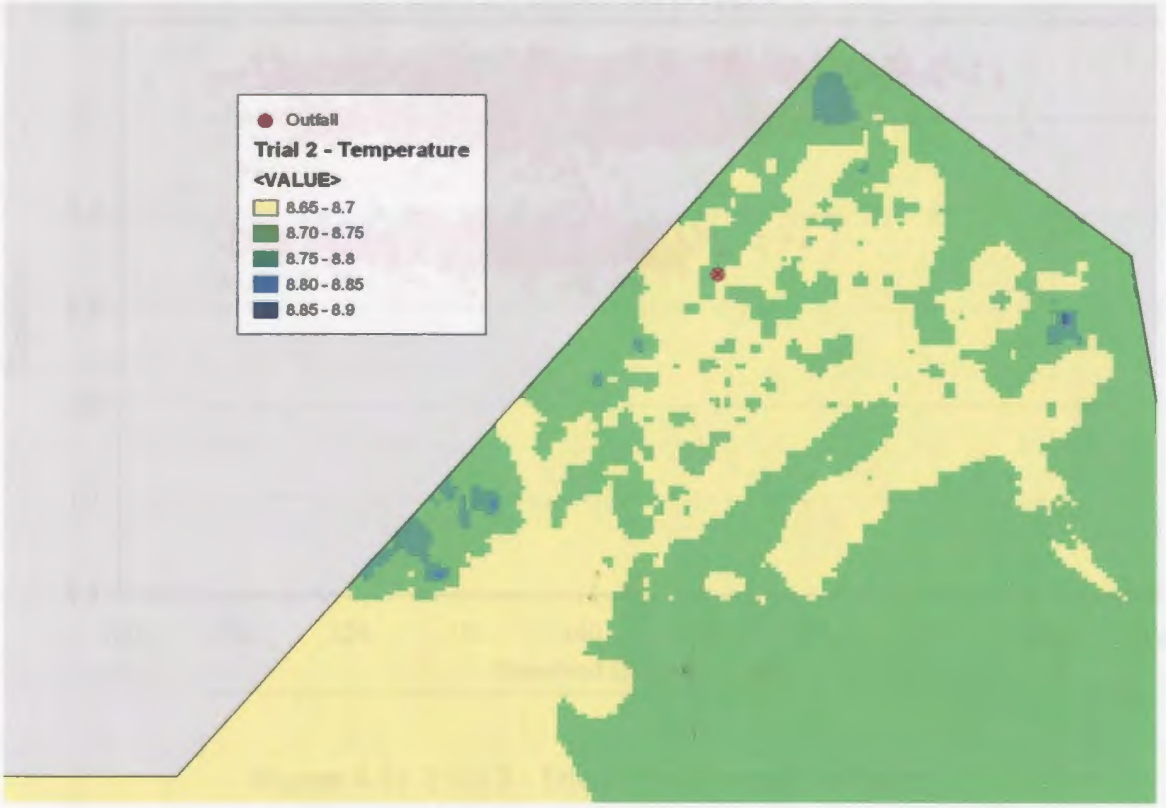

Figure 4.14 Trial 2 - Temperature Profile

4.3.3 Dissolved Oxygen

The dissolved oxygen measurements for Trial 2 are very irregular. From the results represented in Figure 4.10, there appears to be significant noise in the data. However, in the scatter plot (Figure 4.15) it appears to be evenly distributed about the mean for each cast. The range is very large if compared to Trial 1. It is possible to make distinctions between the cast depths. The mean values for each cast are fairly consistent: Cast 6 = 132.56 %, Cast 7 = 140.84 % and Cast 8 = 141.26 %. The DO profile is given in Figure 4.16 and indicates that there are some scattered low and high saturation values which could correspond with the noise in the line plot. However, given the erratic pattern of the line graph, this data should be discarded as the validity should be called into question.

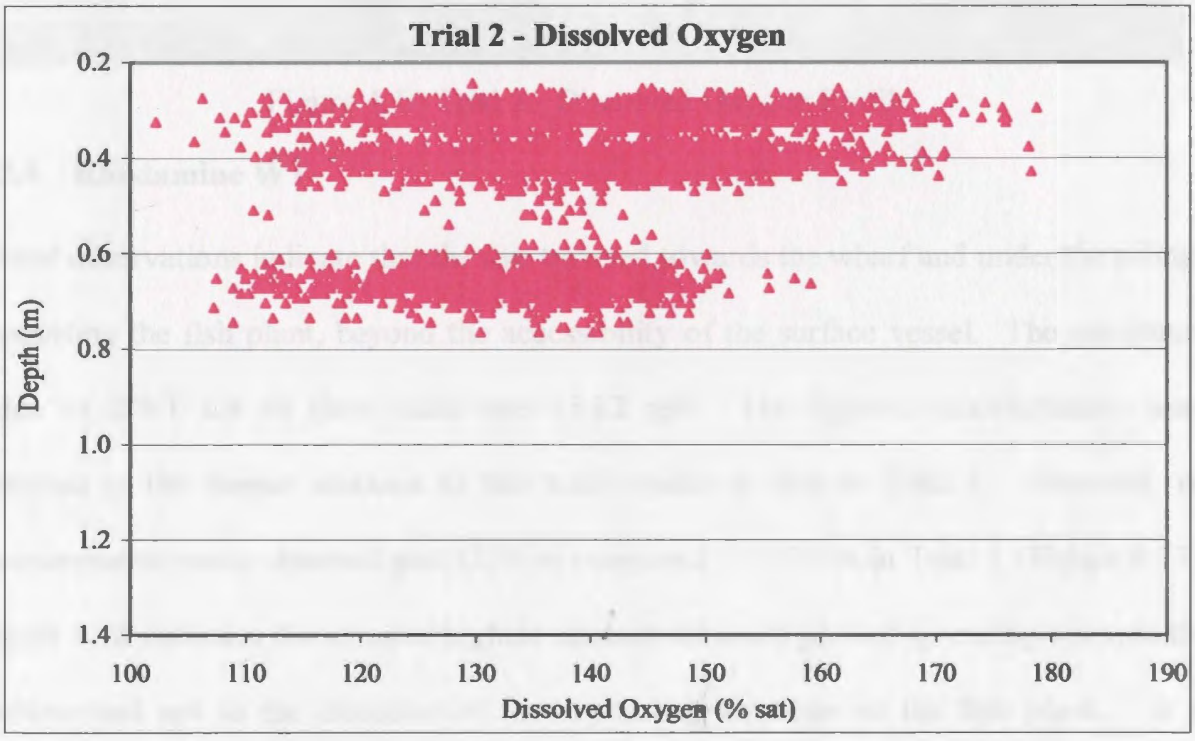

Figure 4.15 Trial 2 - Dissolved Oxygen vs depth

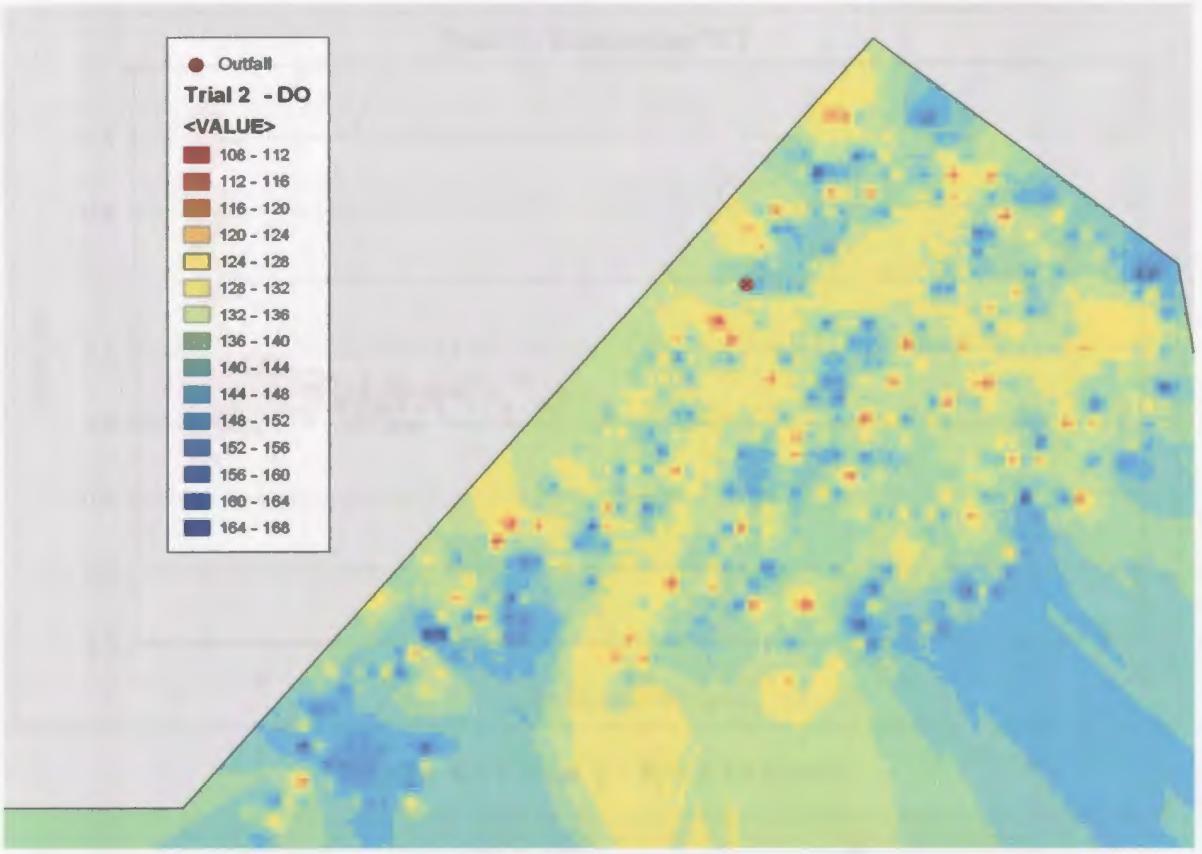

Figure 4.16 Trial 2 - Dissolved Oxygen Profile

4.3.4 Rhodamine WT

Visual observations indicate that the dye traveled towards the wharf and under the pilings supporting the fish plant, beyond the accessibility of the surface vessel. The maximum value of RWT for all three casts was 15.12 ppb. The highest concentrations were obtained at the deeper sections of this trial similar to that of Trial 1. However, no measurements were observed past 0.76 m compared to 1.26 m in Trial 1 (Figure 4.17). Figure 4.18 indicates the areas of highest concentration are plotted spreading towards the harbour and not in the direction of the supporting structure of the fish plant. It is assumed that if the plant wall adjacent to the pipe were a solid structure instead of the current configuration, then the dye would disperse along the wall and wharf.

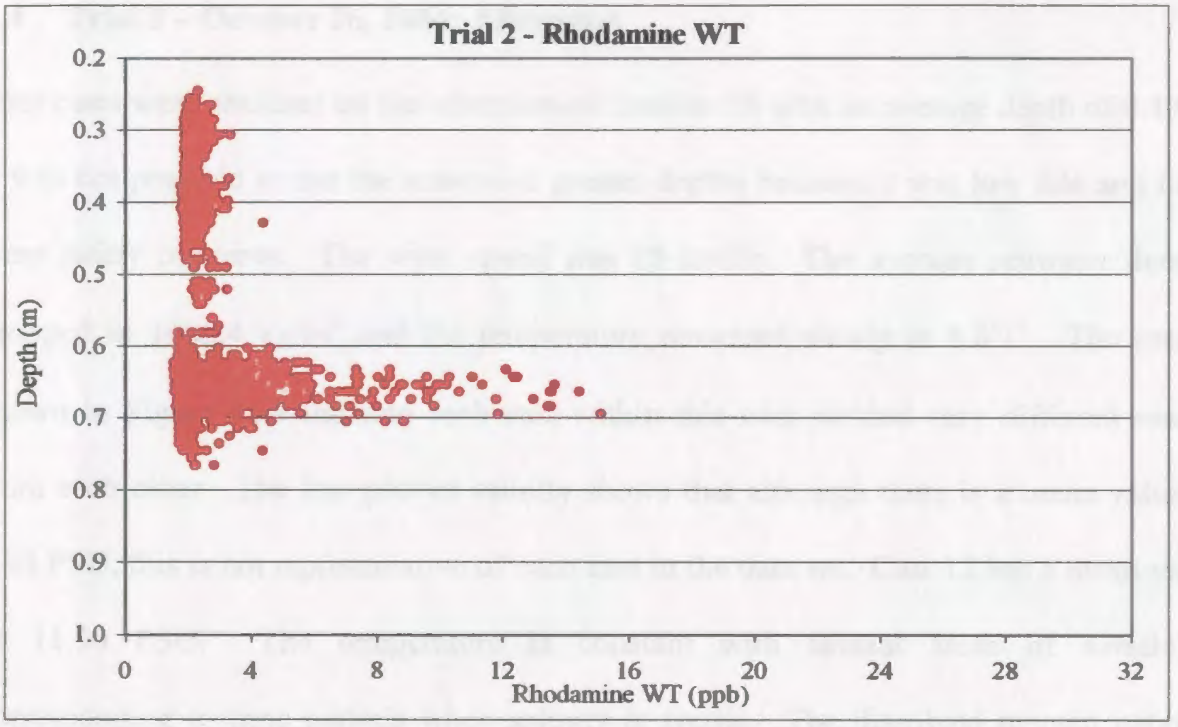

Figure 4.17 Trial 2 - RWT vs Depth

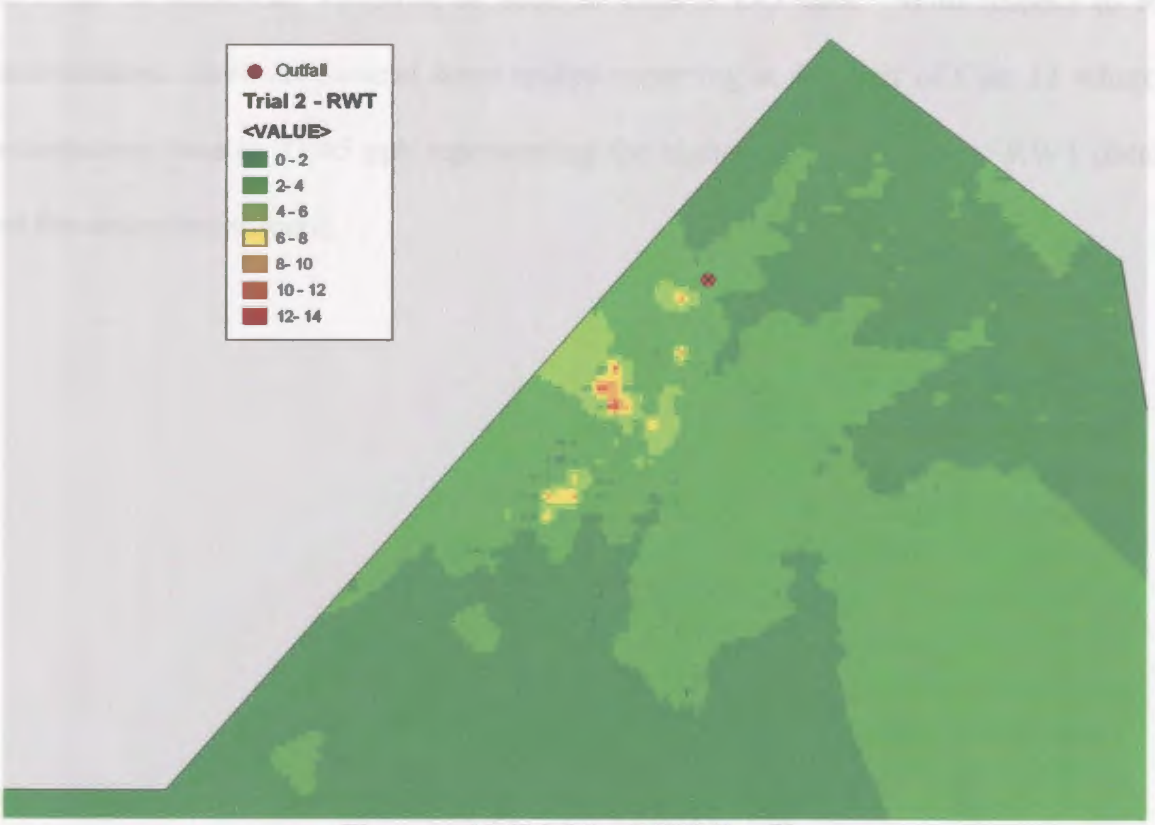

Figure 4.18 Trial 2 - RWT Profile

4.4 Trial 3 – October 26, 2004: Afternoon

Four casts were obtained on the afternoon of October 26 with an average depth of 0.49 m. It was not possible to use the sensors at greater depths because it was low tide and there were safety concerns. The wind speed was 15 km/hr. The average seawater density dropped to 1006.4 kg/m^3 and the temperature remained steady at 8.8°C. The results shown in Figure 4.19 indicate each cast within this trial yielded very different results from each other. The line plot of salinity shows that although there is a mean value of 8.48 PSU, this is not representative of each cast in the data set. Cast 12 has a mean value of 11.90 PSU. The temperature is constant with several areas of variability corresponding to time periods when salinity is erratic. The dissolved oxygen exhibits five areas of noise-like variation as seen in Trial 2 DO data. With respect to RWT concentrations, there are several large spikes occurring at the start of Cast 11 where the concentration rises to 31.45 ppb representing the highest measurement of RWT obtained over the entire experiment.

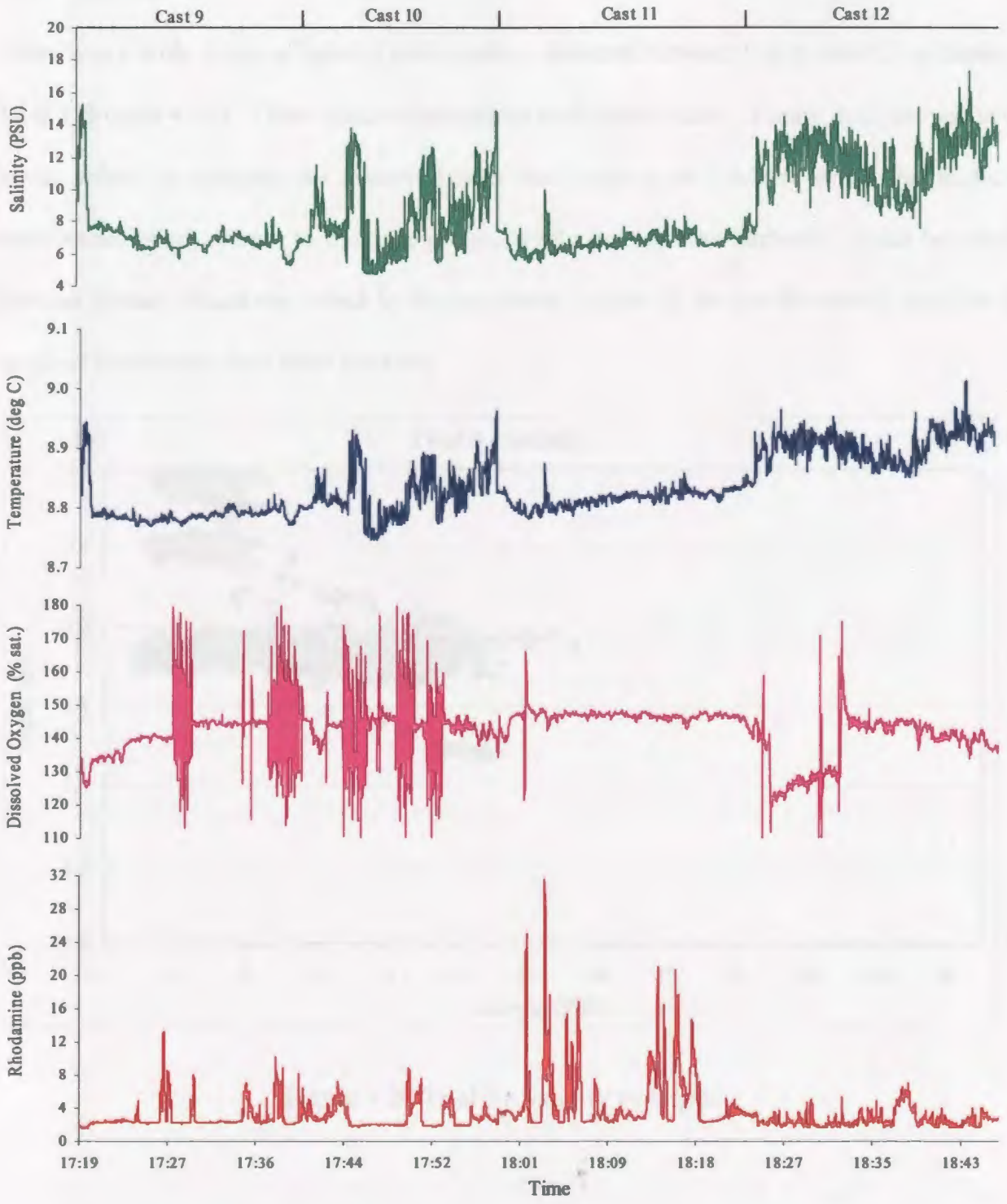

Figure 4.19 Trial 3 - All parameters vs time

4.4.1 Salinity

There was a wide range of salinity observations detected between 0.6 m and 0.7 m during Trial 3 (Figure 4.20). These values correspond to different casts. Figure 4.21 shows that lower values of salinity are observed near the building and wharf while the higher measurements are shown to increase progressively out into the harbour. It can be seen that the lowest values are found in the southwest corner of the profile which may be a result of freshwater flow from the river.

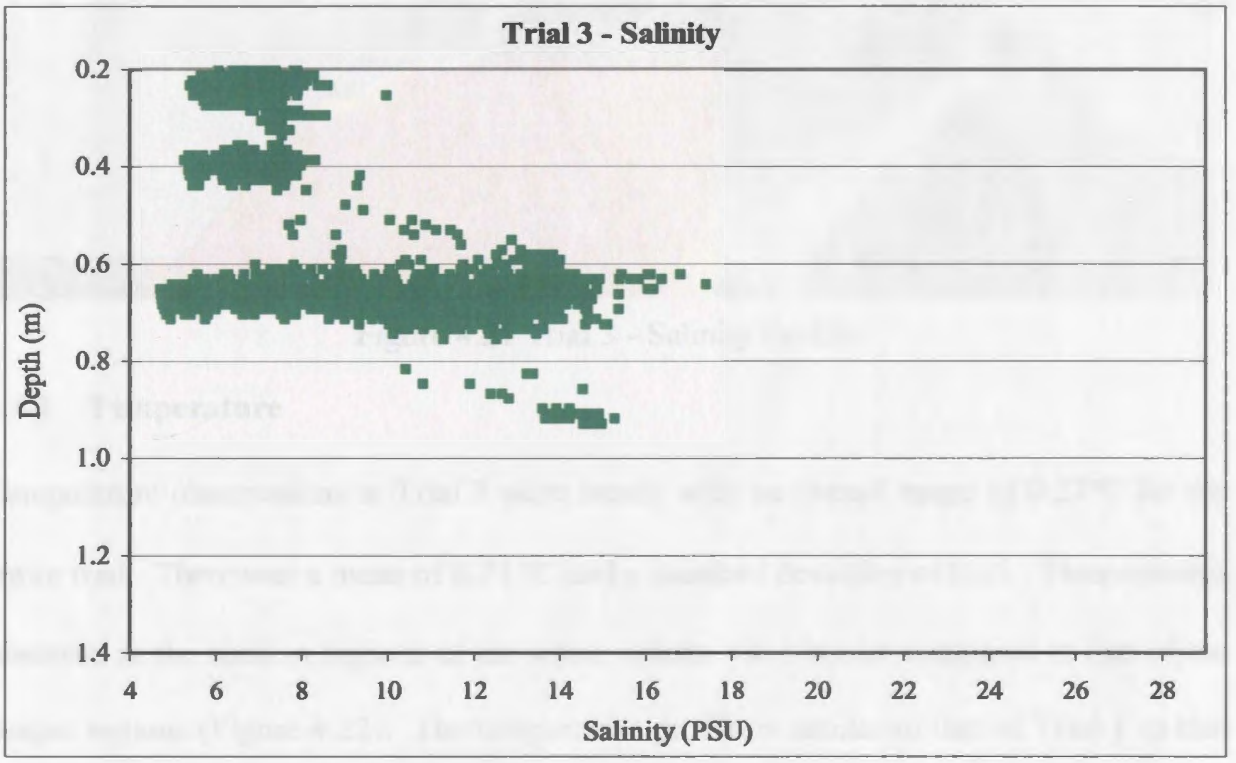

Figure 4.20 Trial 3 - Salinity vs Depth

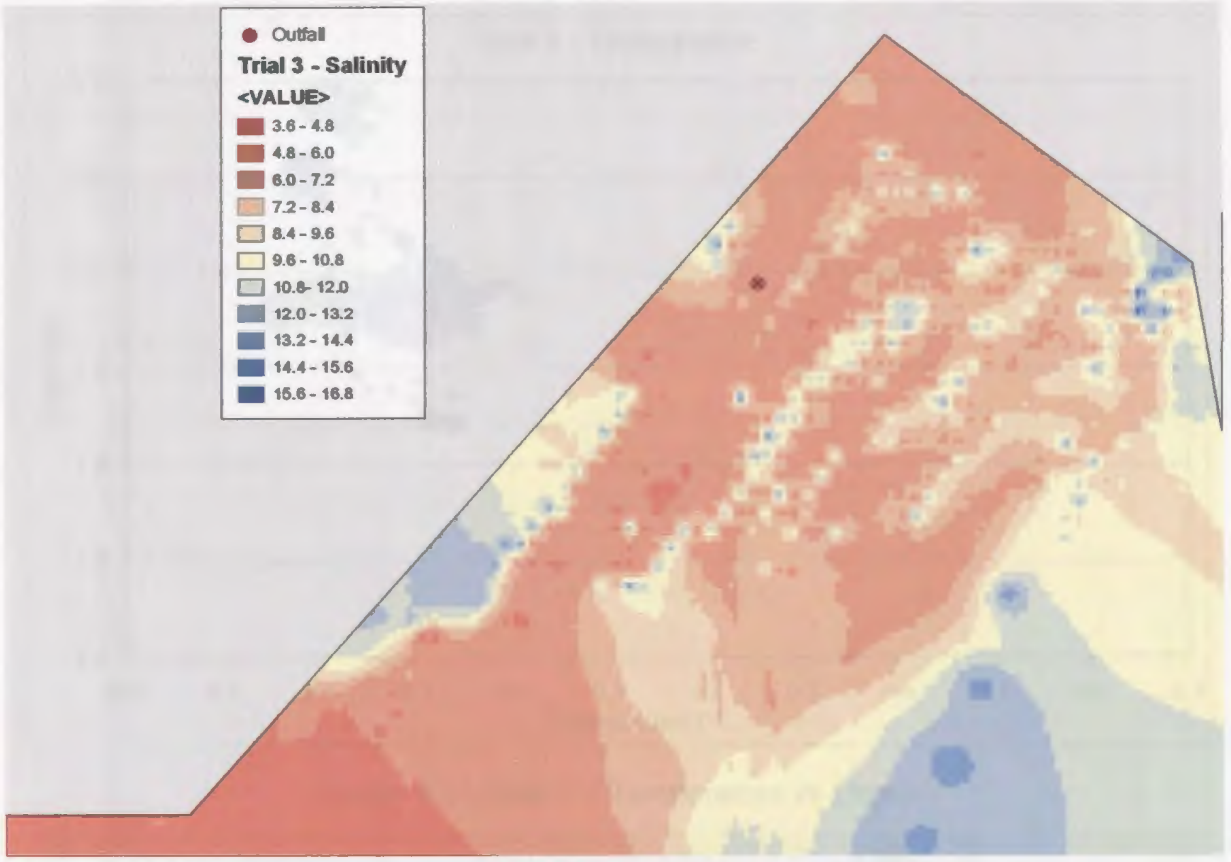

Figure 4.21 Trial 3 - Salinity Profile

4.4.2 Temperature

Temperature observations in Trial 3 were steady with an overall range of 0.27°C for the entire trial. There was a mean of 8.72 °C and a standard deviation of 0.05. Temperatures observed at the shallow regions of the water column were cooler compared to that of the deeper regions (Figure 4.22). The temperature profile is similar to that of Trial 1 in that many cooler observations were obtained in the north corner of the plot (Figure 4.23). This could be attributable to the outfall or the runoff from the wharf and building. Also, the physical properties of colder water are generally heavier and may not move out of the harbour as quickly as the warmer, less dense water.

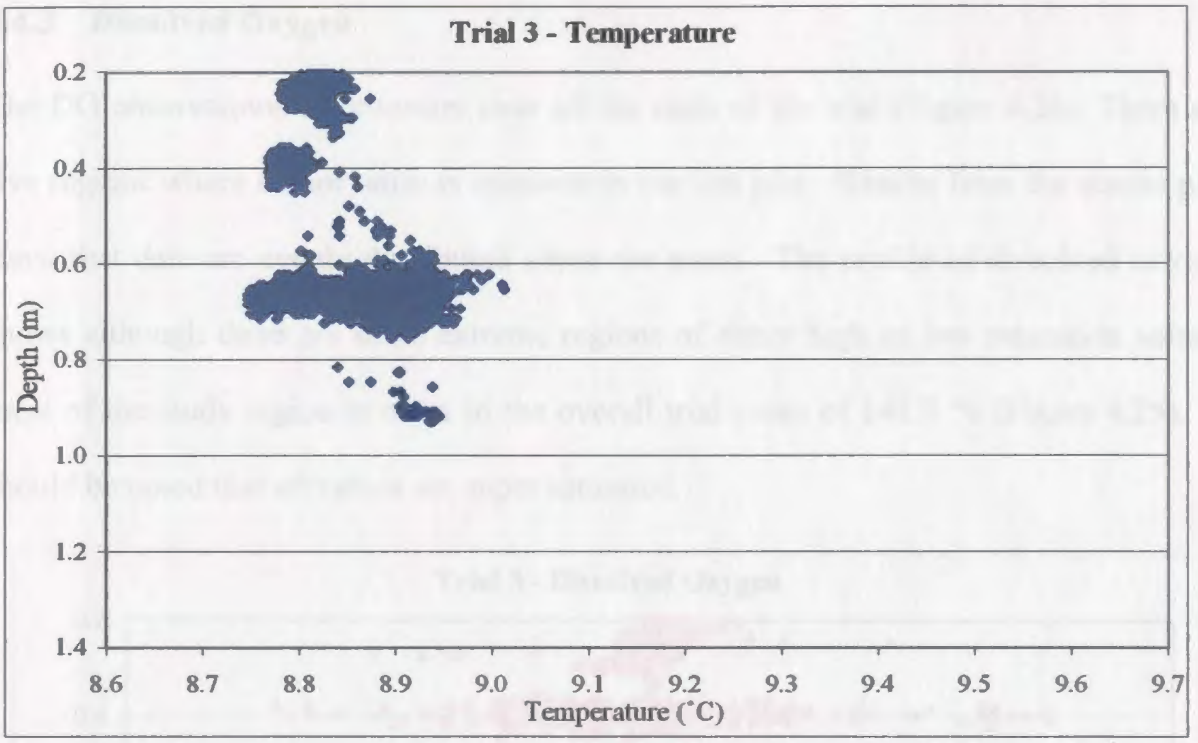

Figure 4.22 Trial 3 - Temperature vs Depth

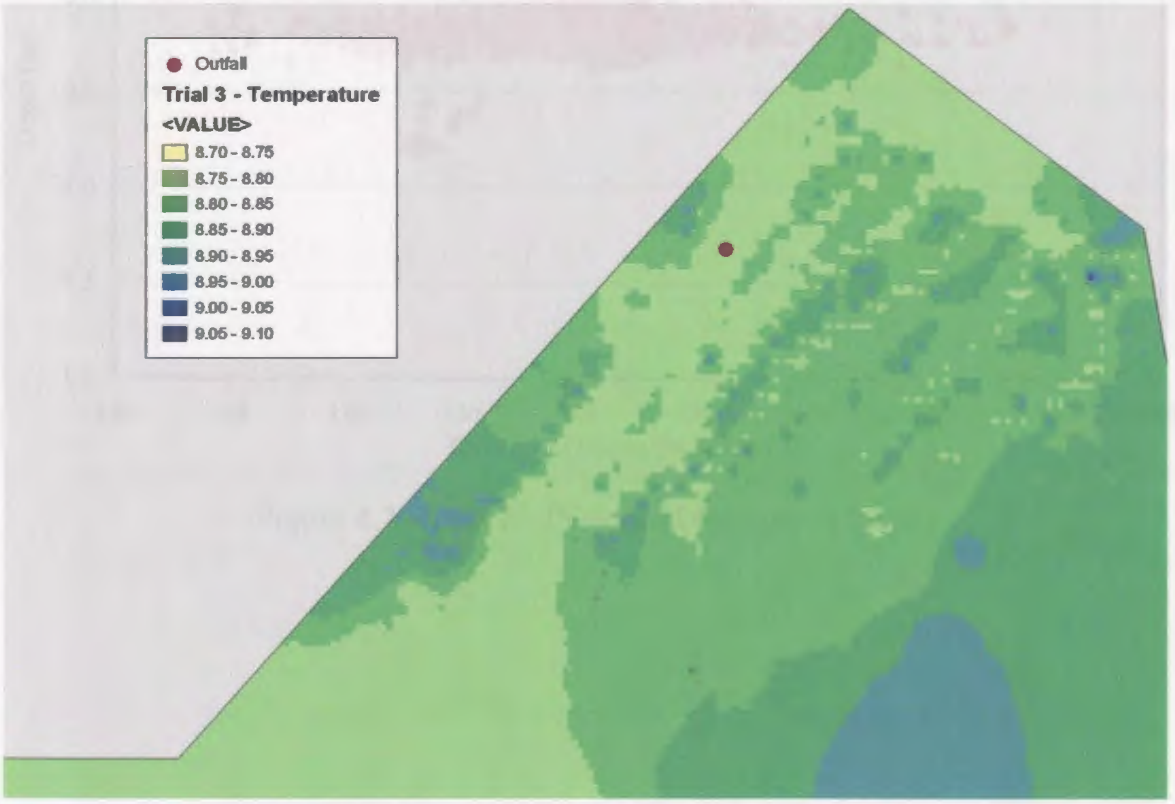

Figure 4.23 Trial 3 - Temperature Profile

4.4.3 Dissolved Oxygen

The DO observations are constant over all the casts of the trial (Figure 4.24). There are five regions where sensor noise is apparent in the line plot. Results from the scatter plot show that data are evenly distributed about the mean. The profile of dissolved oxygen shows although there are some extreme regions of either high or low saturation values, most of the study region is close to the overall trial mean of 141.9 % (Figure 4.25). It should be noted that all values are super saturated.

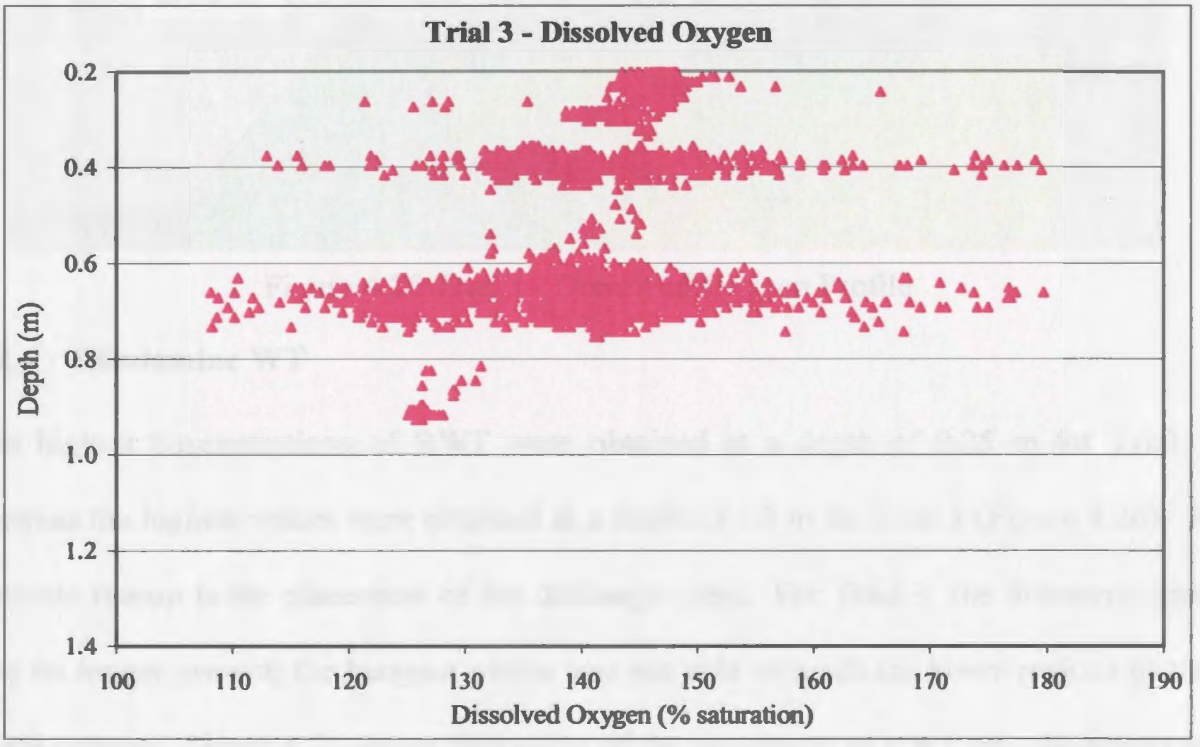

Figure 4.24 Trial 3 - Dissolved Oxygen vs Depth

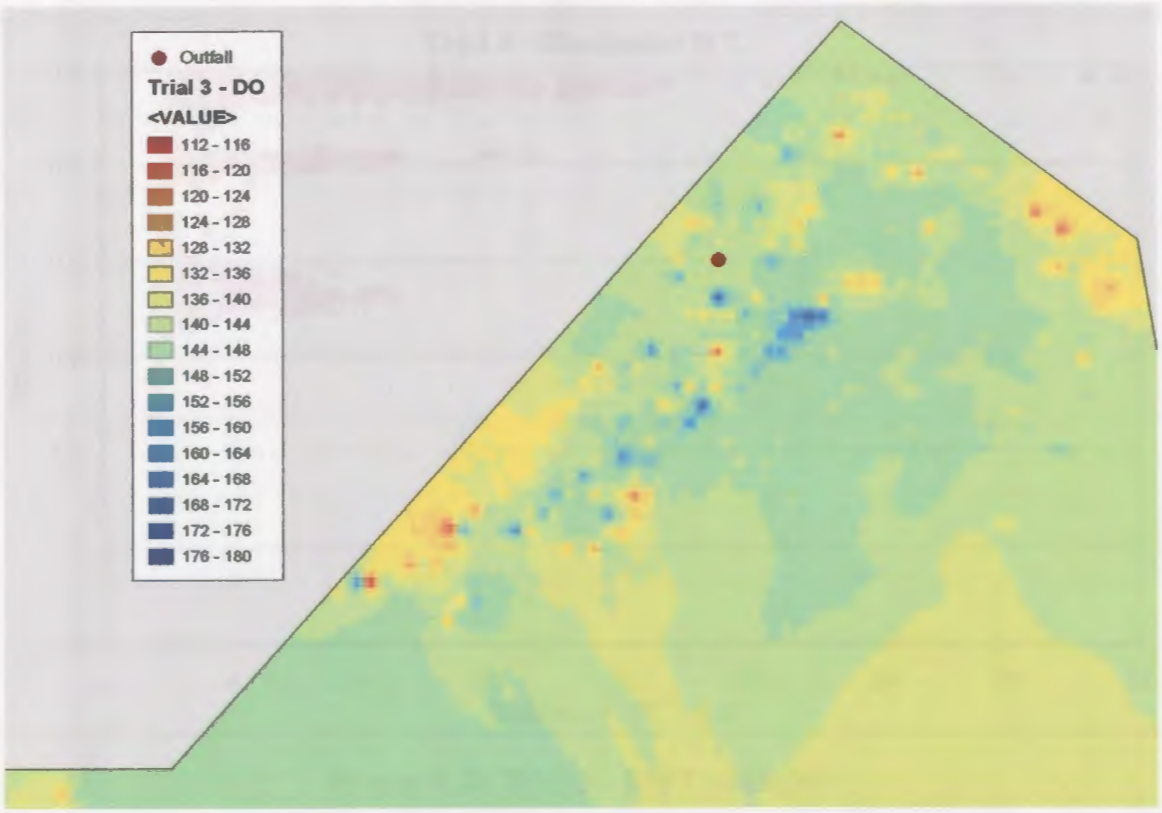

Figure 4.25 Trial 3 - Dissolved Oxygen Profile

4.4.4 Rhodamine WT

The highest concentrations of RWT were obtained at a depth of 0.25 m for Trial 3 whereas the highest values were obtained at a depth of 1.0 m for Trial 1 (Figure 4.26). A possible reason is the placement of the discharge pipe. For Trial 3, the discharge pipe was no longer present; the buoyant plume was not able to reach the lower regions of the water column. Figure 4.27 shows the profile of the movement of RWT into the corner of the wharf and building. The interpolated plot does not appear to fully represent the overall data structure for this trial. There were very few high values measured during this trial, therefore, the interpolation technique does not assign these points with a large weight.

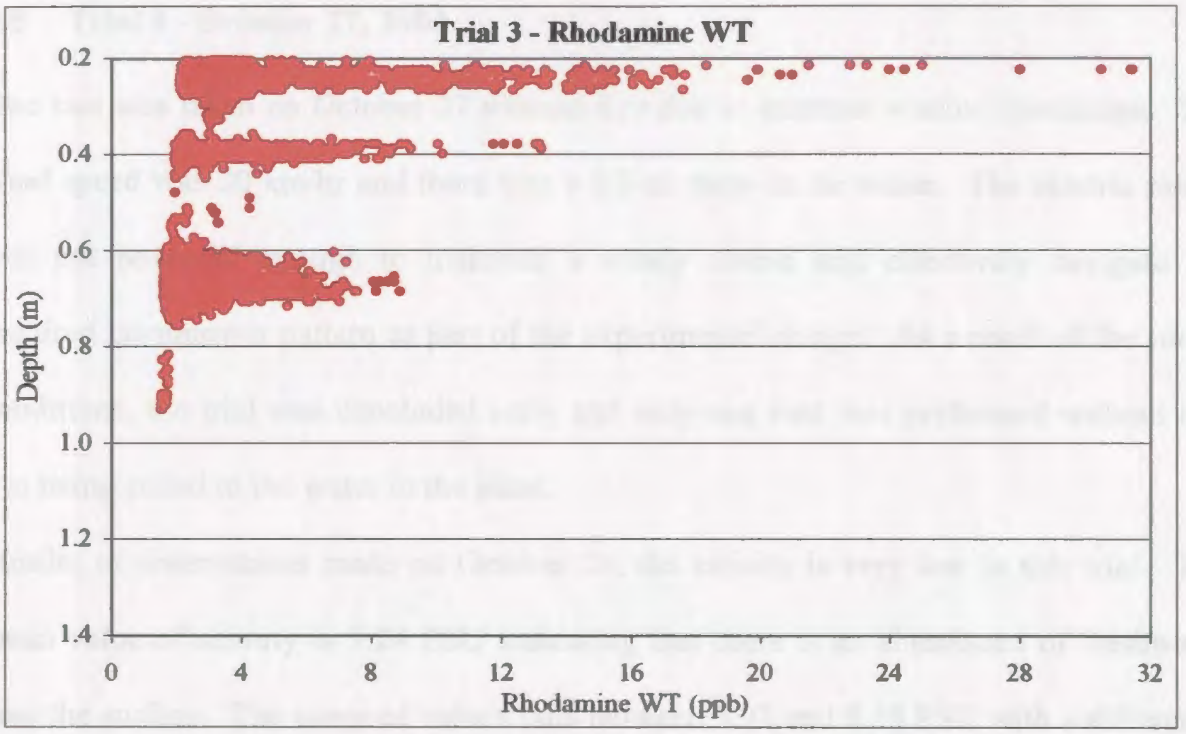

Figure 4.26 Trial 3 - RWT vs Depth

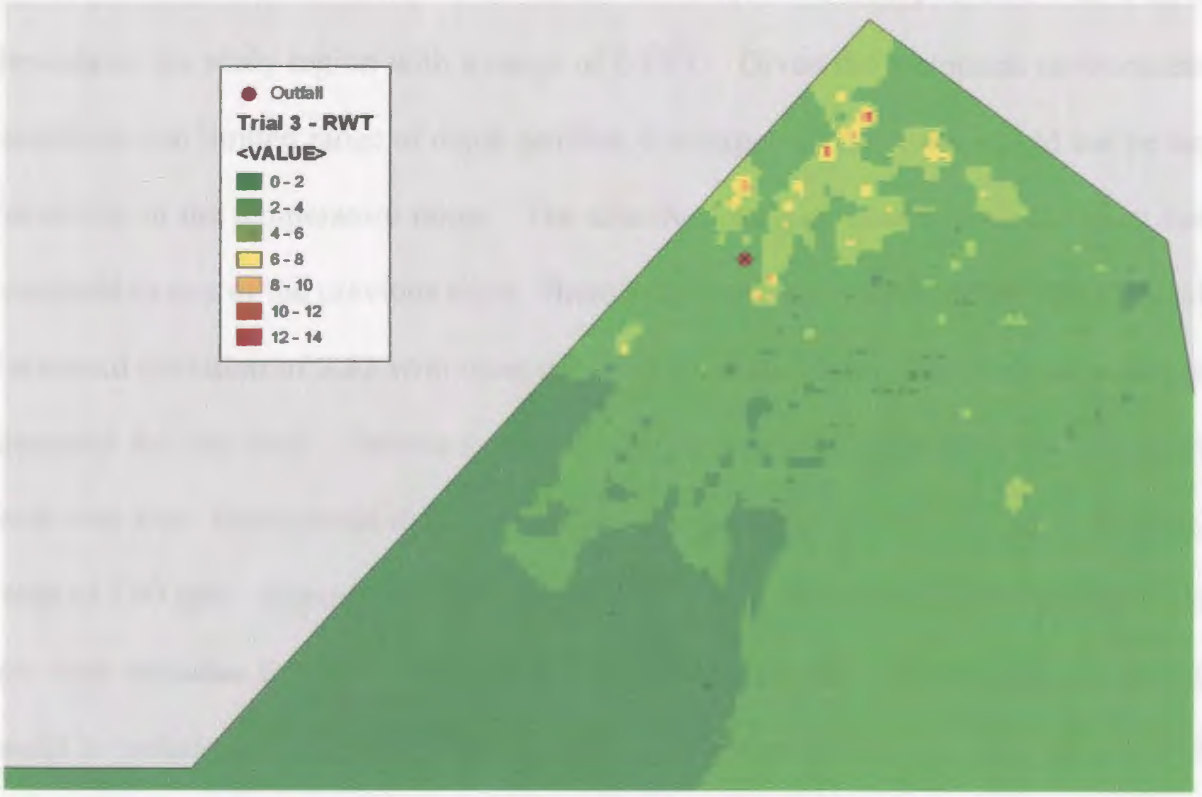

Figure 4.27 Trial 3 - RWT Profile

4.5 Trial 4 - October 27, 2004

One cast was taken on October 27 without dye due to extreme weather conditions. The wind speed was 30 km/hr and there was a 0.5 m chop on the water. The electric motor was not powerful enough to maintain a steady course and effectively navigate the required lawnmower pattern as part of the experimental design. As a result of the rough conditions, the trial was concluded early and only one cast was performed without any dye being added to the water in the plant.

Similar to observations made on October 26, the salinity is very low in this trial. The mean value of salinity is 7.24 PSU indicating that there is an abundance of freshwater near the surface. The range of values falls between 5.93 and 8.33 PSU with a difference of 2.41 and an overall standard deviation of 0.45. The temperature was constant throughout the study region with a range of 0.13°C. Given the inclement environmental conditions and limited range of depth profiles, it is expected that there would not be large variability in the temperature range. The dissolved oxygen observations are very static compared to any of the previous trials. There is a mean saturation level of 144.57 % with a standard deviation of 2.33 with most points close to the mean. No dye was mixed and dispersed for this trial. Therefore, observations of the RWT concentration in this trial were very low. Background dye concentrations range from 1.87 to 2.02 ppb with a mean value of 1.93 ppb. Figure 4.28 represents all the parameters over time for the trial. The raw data indicates that there is little variation in the overall data. It was deemed not useful to include any other plots for this trial in this work due to the static nature of the data and lack of any apparent trends.

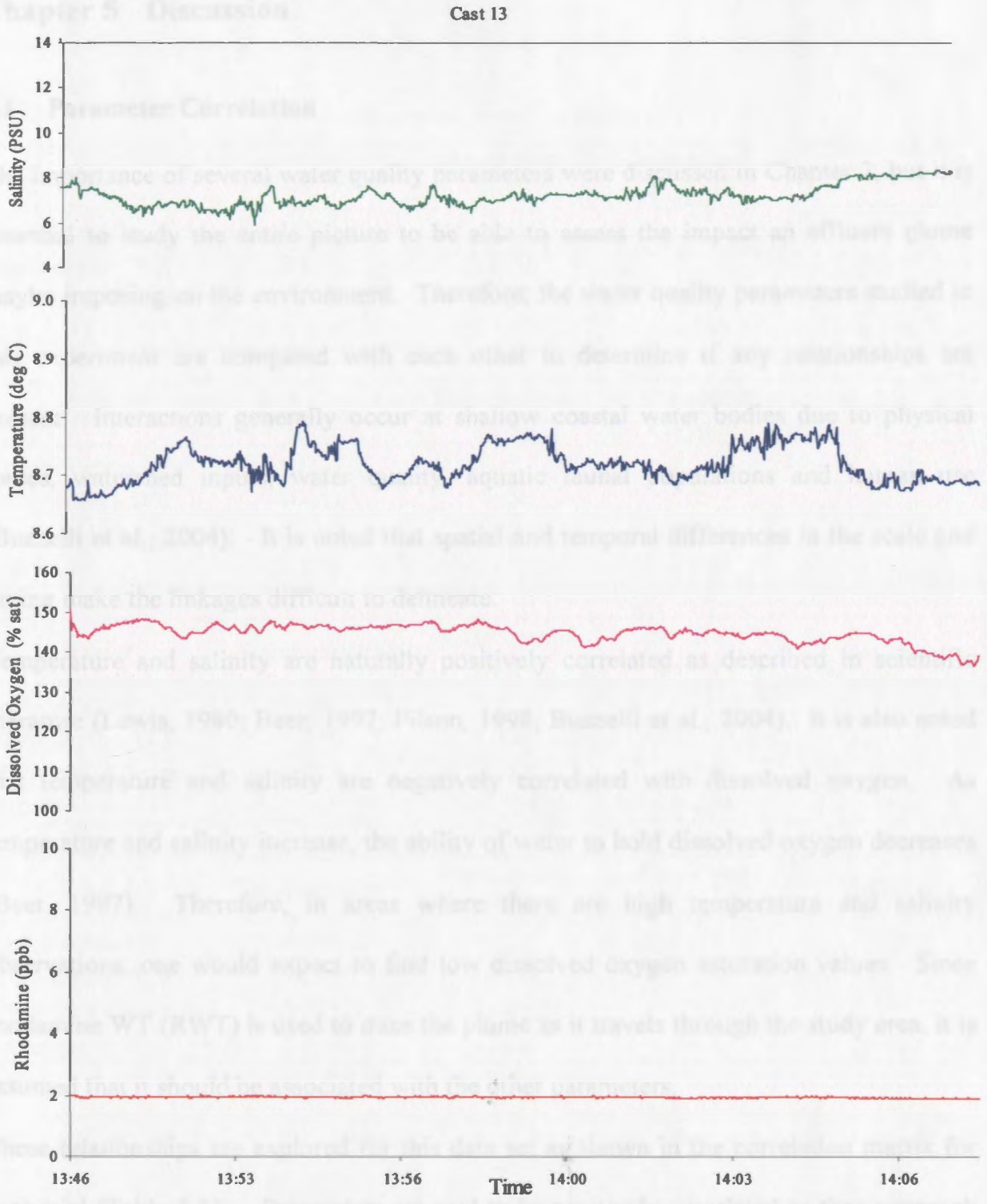

Figure 4.28 Trial 4 - All parameters vs time

Chapter 5 Discussion

5.1 Parameter Correlation

The importance of several water quality parameters were discussed in Chapter 2, but it is essential to study the entire picture to be able to assess the impact an effluent plume maybe imposing on the environment. Therefore, the water quality parameters studied in this experiment are compared with each other to determine if any relationships are present. Interactions generally occur at shallow coastal water bodies due to physical forces, watershed inputs, water quality, aquatic faunal populations and human use (Buzzelli et al., 2004). It is noted that spatial and temporal differences in the scale and timing make the linkages difficult to delineate.

Temperature and salinity are naturally positively correlated as described in scientific literature (Lewis, 1980; Beer, 1997; Pilson, 1998; Buzzelli et al., 2004). It is also noted that temperature and salinity are negatively correlated with dissolved oxygen. As temperature and salinity increase, the ability of water to hold dissolved oxygen decreases (Beer, 1997). Therefore, in areas where there are high temperature and salinity observations, one would expect to find low dissolved oxygen saturation values. Since rhodamine WT (RWT) is used to trace the plume as it travels through the study area, it is assumed that it should be associated with the other parameters.

These relationships are explored for this data set as shown in the correlation matrix for each trial (Table 5.1). Parameters are said to be positively correlated as they approach

+1 and negatively correlated as the approach -1. There is little or no correlation as the correlation coefficient approaches 0.

Table 5.1 Correlation matrix for all trials

Trial 1	**Temperature**	**Rhodamine WT**	**Dissolved Oxygen**	**Salinity**
Temperature	1.000			
Rhodamine WT	0.171	1.000		
Dissolved Oxygen	-0.667	0.133	1.000	
Salinity	0.940	0.121	-0.650	1.000
Trial 2	**Temperature**	**Rhodamine WT**	**Dissolved Oxygen**	**Salinity**
Temperature	1.000			
Rhodamine WT	-0.034	1.000		
Dissolved Oxygen	-0.039	-0.044	1.000	
Salinity	0.199	0.178	-0.371	1.000
Trial 3	**Temperature**	**Rhodamine WT**	**Dissolved Oxygen**	**Salinity**
Temperature	1.000			
Rhodamine WT	-0.150	1.000		
Dissolved Oxygen	-0.394	0.215	1.000	
Salinity	0.955	-0.228	-0.489	1.000
Trial 4	**Temperature**	**Rhodamine WT**	**Dissolved Oxygen**	**Salinity**
Temperature	1.000			
Rhodamine WT	0.233	1.000		
Dissolved Oxygen	0.033	0.482	1.000	
Salinity	-0.535	-0.608	-0.673	1.000

Observations in Trial 1 demonstrate some characteristic relationships that would be expected in this type of analysis. Temperature and salinity have a strong positive correlation. This relationship is described further in Figure 5.1, whereby most data are

scattered close to the linear trend line. Since temperature and salinity are strongly correlated, it follows that they are both negatively correlated to dissolved oxygen (-0.667 and -0.650 respectively). The RWT concentration has a slight positive relationship with all of the other parameters with the closest correlation being with temperature at 0.171. The RWT profile shows that it is not spatially correlated to the other parameters as all other parameters have a distinctive plume along the building to the southwest corner of their respective profiles while RWT moves out towards the outer harbour, to the southeast. The correlation coefficient confirms this finding as the physiochemical properties of RWT are not associated with temperature, salinity or dissolved oxygen.

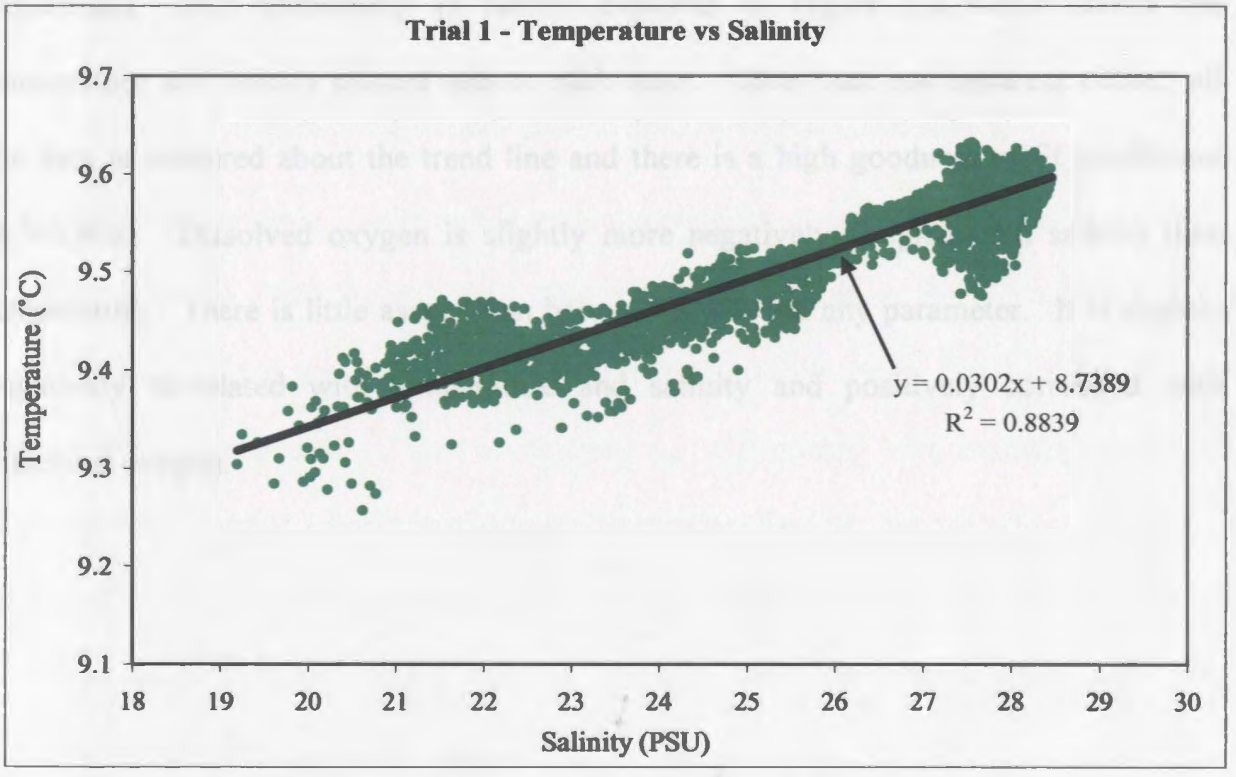

Figure 5.1 Trial 1 - Temperature and salinity regression analysis

Trial 2 has poor correlative properties between all parameters. Temperature and salinity have a small positive relationship as noted in their respective profiles and the lower than expected correlation coefficient (0.199). The relationship with dissolved oxygen is negatively correlated as expected in salinity (-0.371) but very weakly correlated with temperature (-0.039). RWT is only slightly positively correlated with salinity (0.178) and does not show any significant relationship with the other parameters. It is postulated that the majority of the plume traveled underneath the plant to areas that were not accessible by the boat.

The temperature and salinity relationship found in Trial 3 is the strongest for the entire experiment. This relationship is further explored in Figure 5.2 which shows the temperature and salinity plotted against each other. Other than one apparent outlier, all the data is scattered about the trend line and there is a high goodness of fit coefficient (R^2=0.908). Dissolved oxygen is slightly more negatively coupled with salinity than temperature. There is little association between RWT and any parameter. It is slightly negatively correlated with temperature and salinity and positively correlated with dissolved oxygen.

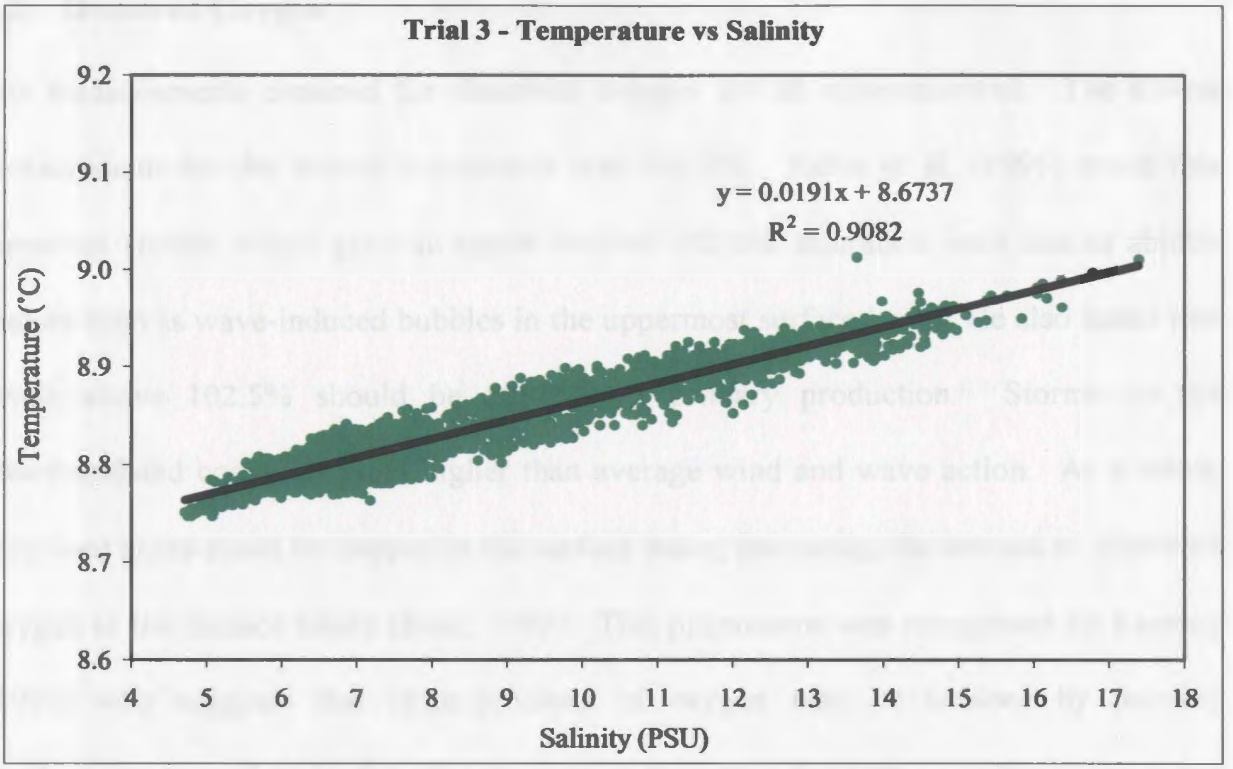

Figure 5.2 Temperature and salinity regression analysis

The data obtained from Trial 4 was essentially baseline data as no dye was injected into the system due to weather conditions. The relationships achieved for this data set are not similar to any of the previous trials. Temperature and salinity are negatively correlated, which was not expected. There is virtually no relationship between temperature and dissolved oxygen but a fairly strong negative relationship between salinity and dissolved oxygen. Finally, RWT concentrations have a correlation between dissolved oxygen and salinity, yet no RWT was used that day. It is assumed that the weather and surface conditions have yielded erratic results.

5.2 Dissolved Oxygen

The measurements obtained for dissolved oxygen are all supersaturated. The lowest measurement for the overall experiment was 102.3%. Rahm et al. (1995) noted that empirical studies which gave an upper limit of 102.5% saturation were due to abiotic factors such as wave-induced bubbles in the uppermost surface layer. He also stated that levels above 102.5% should be due to net primary production. Storms on the Newfoundland coast can yield higher than average wind and wave action. As a result, dissolved gases could be trapped in the surface water, increasing the amount of dissolved oxygen in the surface layers (Beer, 1997). This phenomena was recognized by Ramsey (1962) who suggests that large amounts of oxygen may be induced by primary productivity as well as by the efficient mixing processes that continuously expose water to atmospheric exchange. If a site is exposed to the open sea it can be profoundly influenced by water advected into the area by the local coastal drift, tidal currents and wind-driven circulation (Ramsey, 1962). However, it was noted that during seasons when phytoplankton blooms are common, the relative influence of the biological and physical conditions upon oxygen distribution is difficult to assess.

All measurements were recorded at the surface layer of a shallow coastal area. Ramsey (1962) noted that oxygen saturations in the upper 20 ft (6.1 m) tend to remain supersaturated at all times. Aquaforte Harbour is fairly exposed and shallow in the area of the fish plant, reaching a depth of 5 m at the end of the wharf. Since circulation in this shallow harbour is good, dissolved oxygen levels should be high.

Another factor that may lead to the supersaturation of the surface waters is the amount of freshwater in the harbour. It is noted from the overall data analysis that salinity was low. Also, temperature is low which tends to yield greater potential for oxygen saturation. The river upstream from the fish plant is considered a good source of oxygenated water that is continually flowing into the coastal zone. The region is sparsely populated with little industrial activity making this river runoff relatively unpolluted and rich in oxygen and nutrients. Furthermore, during a storm on October 24, a large volume of freshwater would have poured into the harbour from the river due to rainfall resulting in increased volume of freshwater deposited into the harbour.

The fish plant was not operational for two months prior to the experiment. It is assumed that the residual effects of the large organic input of the fish plant effluent had dissipated by the time of the tests. Potential excess nutrients resulting from the fish plant waste would have been used in a natural fall algal bloom which would result in higher oxygen levels in optimal conditions.

However, due to the erratic nature of the results obtained during Trial 2 and several sections of Trial 3, it should be noted that there may have been interference with the sensor signal. Sensor malfunction during these periods could also be an explanation for the skewed observations.

5.3 RWT Plume Analysis

Further analysis is conducted with the RWT observations for Trial 1 as the RWT measurements yielded the best results in delineating a plume. The RWT data was compared to the dilution model CORMIX to determine if the model could make an

accurate prediction of the observed results. At the time of the experiment ambient current information was not available. This parameter is a key component of the input to the CORMIX model; therefore, several iterations were completed to estimate the most accurate representation of the ambient conditions. Since all casts were conducted during a period of roughly 1.5 hours, steady current conditions were assumed for the purposes of simplification.

5.3.1 Plume Line Derivation

Comparison of the observed and predicted results requires further manipulation of the data. CORMIX prediction results are given in the form of dilution and concentration of the effluent with respect to the distance of the center of the plume from the source or centerline. In order to compare these predicted results to the observed data, the distance of each point in the study area from the outfall location must be determined. This task was completed by converting the raster image back to vector data thereby creating a point to represent each grid cell for the entire study area instead of the patchy distribution previous to the interpolation process. The distance from the outfall location to all cells over the entire study area was calculated and joined to the attribute data of each point yielding information on the distance and concentration for each point. Next, a boundary polygon was created to facilitate the removal of the points that were interpolated in the location of the plant and wharf. No measurements were conducted beyond these features so the estimates for these regions were meaningless and were removed.

The plume centerline was estimated through a multi-step process. The initial step was to create a line feature that followed the area of highest concentration away from the outfall

location continuing away from the source to the extent of the study area. The line was not started at the exact location of outfall but at the highest intensity of dye. The Garmin 76 GPS unit has an accuracy of <15 m in the configuration used for this experiment (Garmin, 2001); therefore, it was logical to place the start of the plume relative to the other points rather than the arbitrary, potentially inaccurate point. Next, a 1 m buffer region was created around the line to select the points that should be considered as part of the plume. The attributes of the plume features (i.e. concentration and distance) were exported to a spreadsheet for analysis. The RWT data and estimated plume centerline are shown in Figure 5.3.

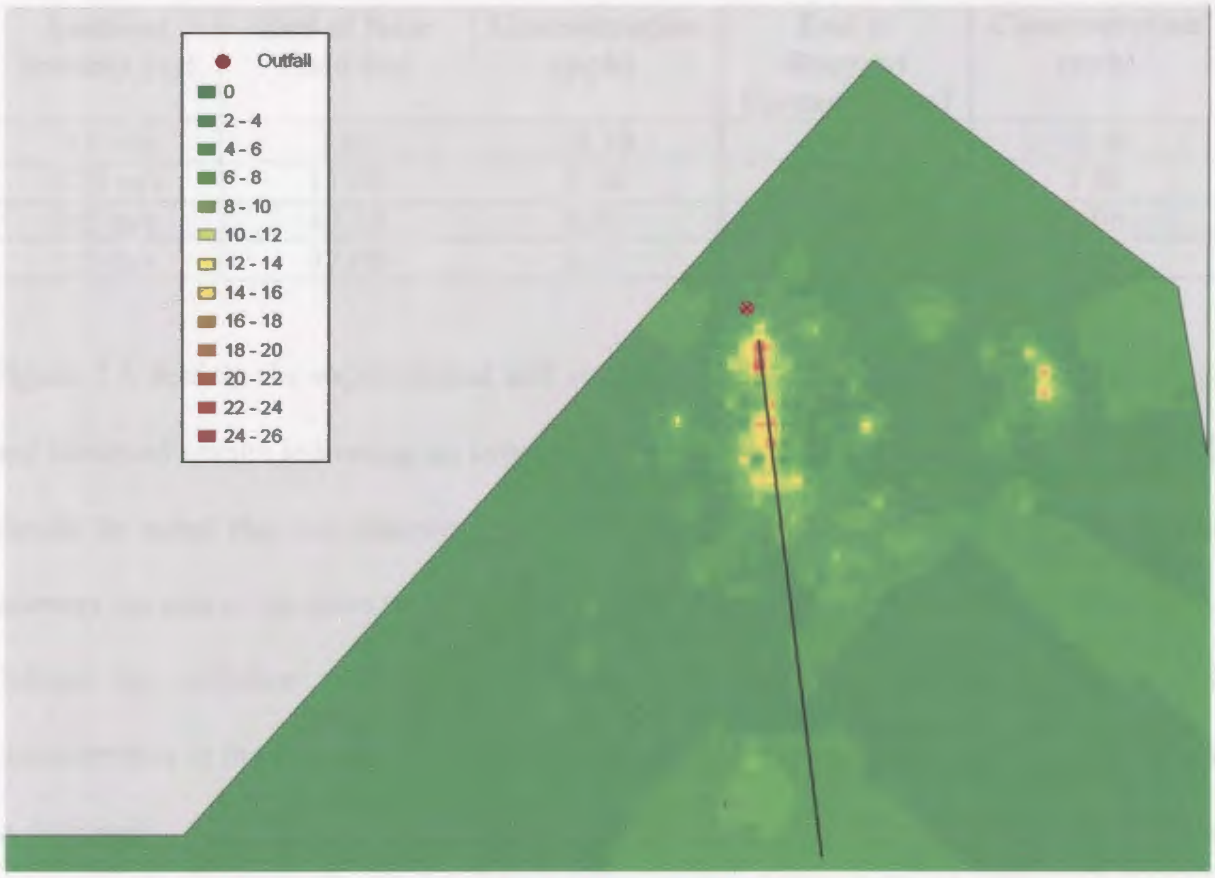

Figure 5.3 Trial 1 RWT observations and estimated plume

5.3.2 Model Comparison

CORMIX 1 iterations were conducted by using four ambient velocities (u_a): 0.1 m/s, 0.25 m/s, 0.5 m/s and 0.7 m/s to determine the best possible fit to the observed data. Due to small effluent discharge rate, the CORMIX 1 software did not allow the input of ambient current velocities higher than 0.7 m/s and lower values yielded unrealistic results. A summary of the CORMIX 1 results is shown in Table 5.2. The prediction results including the various input and calculated parameters used in the model calculation are found in Appendix D.

Table 5.2 CORMIX 1 Iteration Results

Ambient Velocity (u_a)	End of Near Field (m)	Concentration (ppb)	End of Buoyant Spreading (m)	Concentration (ppb)
0.1 m/s	7.60	13.10	9.16	12.40
0.25 m/s	11.00	8.08	12.60	7.96
0.5 m/s	19.39	5.01	45.49	2.06
0.7 m/s	37.66	2.07	175.00	0.15

Figure 5.4 depicts the experimental and simulated data from the CORMIX 1 iterations and observed results indicating an exponential trend away from the source in all cases. It should be noted that the observed results did not extend beyond 60 m from the source whereas the end of the zone of dilution was fixed at 175 m for CORMIX1 simulations (as defined by software requirements as the smallest region possible). The highest concentration in the observed data is less than 30 ppb whereas all simulated plumes begin at 500 ppb. Also, 10 to 20 m from the outfall source the observed concentrations are higher than that of all the simulated results.

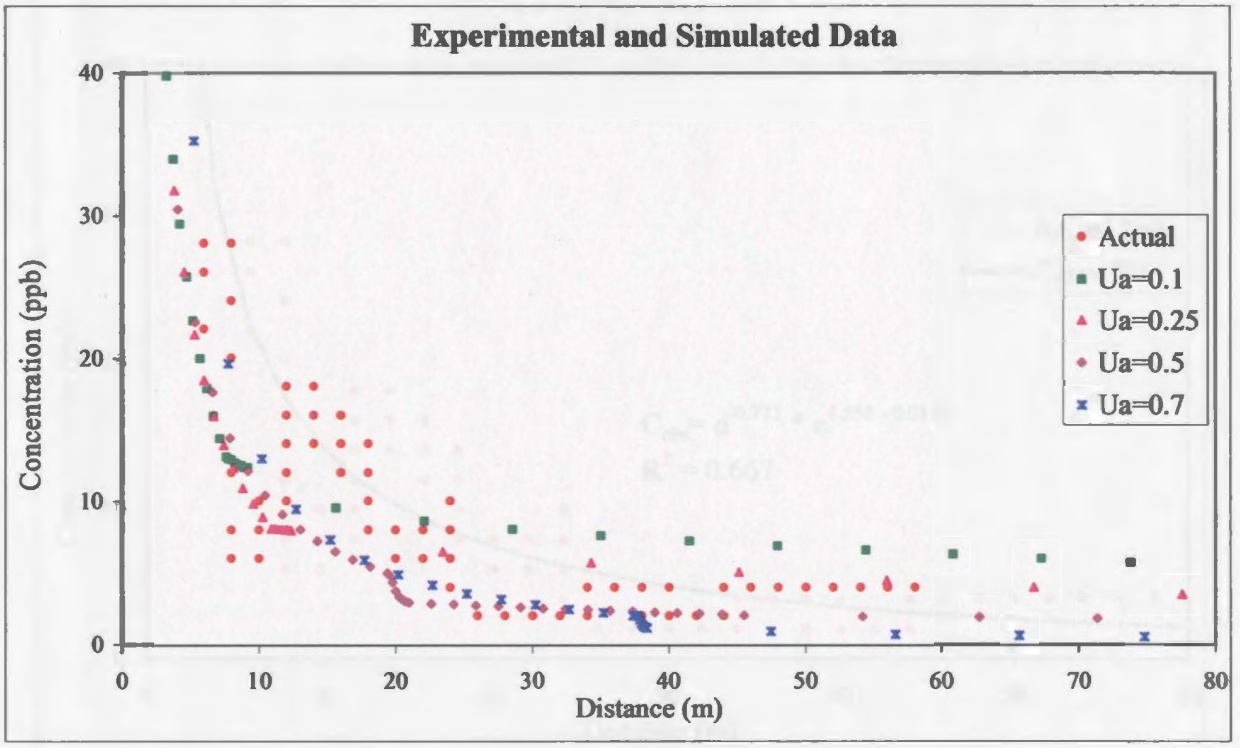

Figure 5.4 Experimental and simulated data

The data was fitted to a curve through an iterative process to identify an appropriate and close fitting line using DataFit™ software (Figure 5.5). The resultant equation is of the following form:

$$C_{obs} = d^{-0.773} \cdot e^{(4.558 - 0.0108d)} \qquad [6]$$

where C_{obs} represents the observed concentration and d represents the centerline distance from the source. This equation represents an approximation to the observed results within a certain degree of error. The goodness of fit coefficient is fairly high for environmental data ($R^2 = 0.667$).

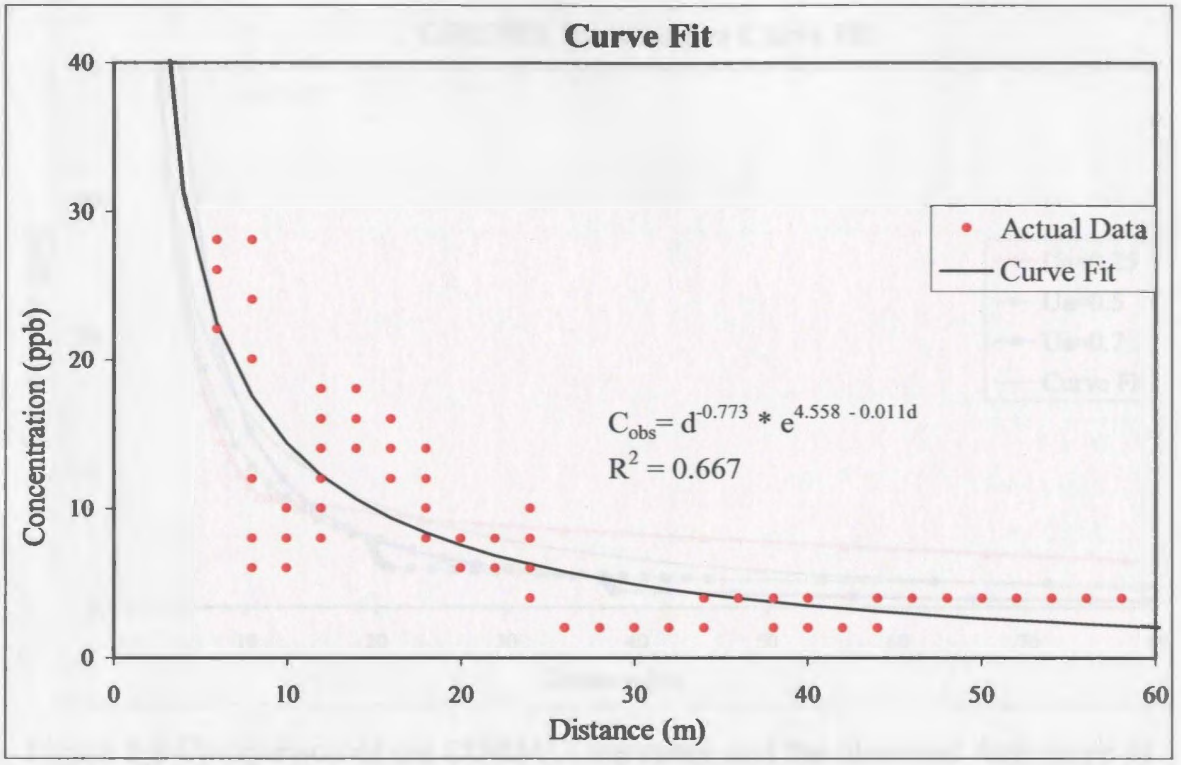

Figure 5.5 Observed data curve fit

The CORMIX iterations closely related to the actual data through a visual comparison were selected for further analysis by connecting the data points (Figure 5.6). It was concluded that 0.1 m/s would be least likely fit the observed concentration range as its values were too high in the near field and far field regions. The iterations for u_a = 0.25 m/s, u_a = 0.5 m/s and u_a = 0.7 m/s were found to represent the curve fitted line most closely over the whole plume range. Both 0.25 and 0.5 m/s iterations appear to emulate the data curve in the near field. The predicted plume estimated with the ambient velocity of 0.5 m/s is very similar to that of the observed plume line in far field region following the transitional region of the plume.

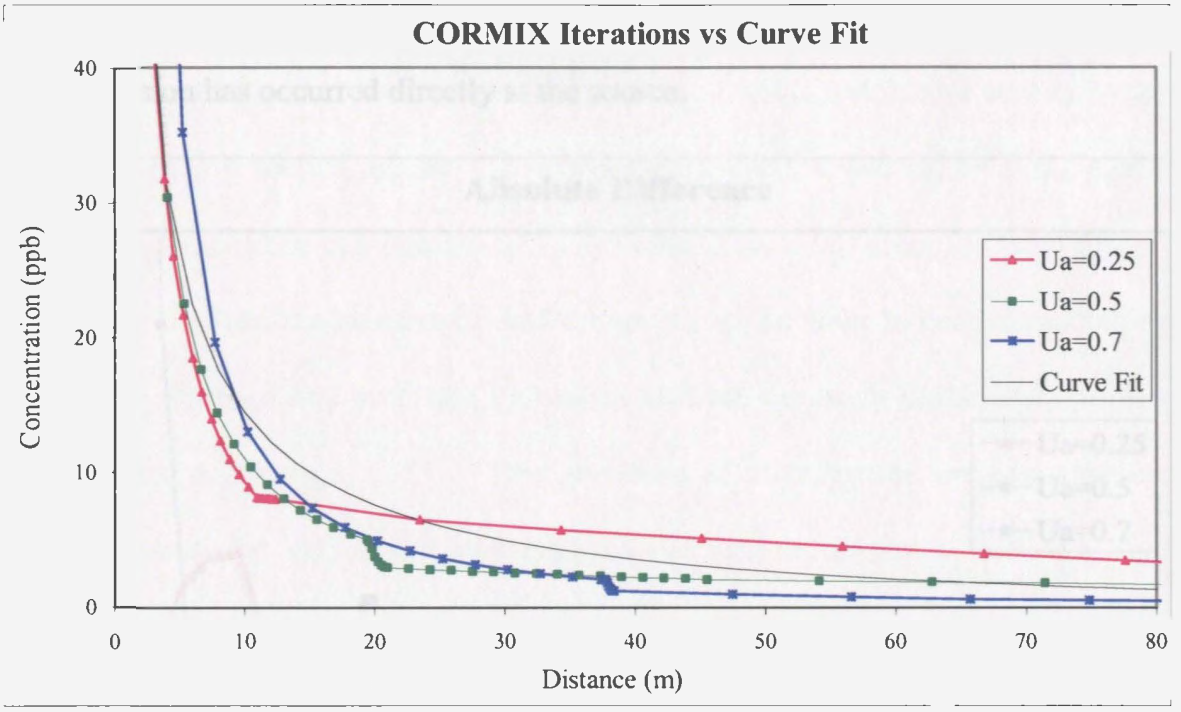

Figure 5.6 Comparison of the CORMIX iterations and the observed data curve fit

Figure 5.7 indicates the absolute relative difference between the actual concentration and the predicted concentration using the actual data's curve fit equation. The iteration with the lowest relative difference changes as the distance increases from the source. Initially, u_a =0.25 and 0.5 have a sudden downward spike then the difference increases in the transition zone. The absolute difference trend for 0.25 m/s decreases to zero following the transitional zone then increases to an average of ±2 ppb in the far field region. The iteration, u_a =0.5 was very similar to that of the 0.25 iteration in the near field region, but decreases to near zero in the far field region which is beyond the point of any experimental results. For the highest velocity iteration, u_a =0.7, the near field region's absolute difference is larger than the other two iterations. Since the transitional zone occurs much later than the other iterations the line appears to be shifted. There is a

lower overall absolute difference, with the highest difference being ±2.6 ppb, once the initial dispersion has occurred directly at the source.

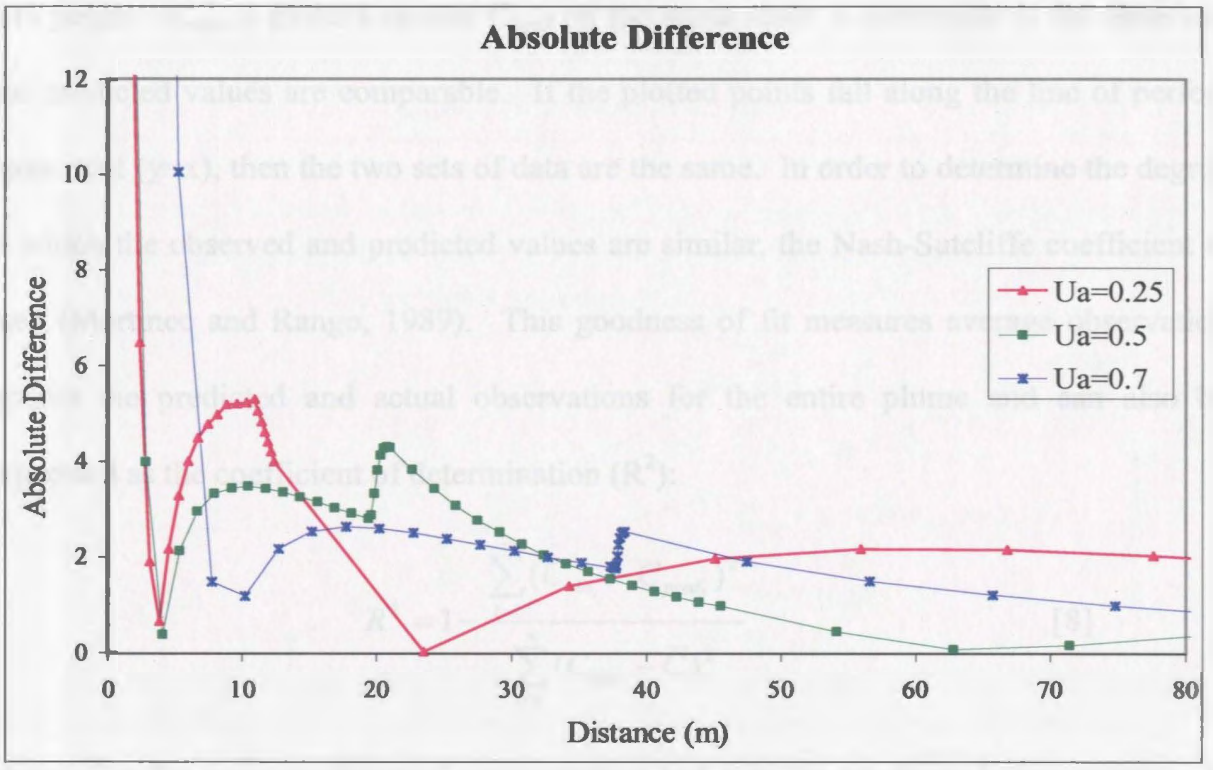

Figure 5.7 Absolute difference of predicted and observed values

A regression analysis was also used to compare the CORMIX model to the observed results from Trial 1. The regression equation is in the form (Kananto, 1993):

$$C_{obs_i} = a + bC_{pred_i} + e_i \qquad [7]$$

where C_{obs_i} represents the observed concentration while C_{pred_i} represents the predicted concentration derived from CORMIX 1. Similar to standard equation of a line, a is the constant term or y-intercept, b stands for the regression coefficient or slope and e_i is the term for random error.

This equation is utilized to estimate the standard ordinary least squares method. If there is perfect agreement between C_{obs} and C_{pred}, then $C_{obs}=C_{pred}$, a=0, b=1 and $e_i=0$ for all data points. C_{obs} is plotted against C_{pred} on the same scale to determine if the observed and predicted values are comparable. If the plotted points fall along the line of perfect agreement (y=x), then the two sets of data are the same. In order to determine the degree to which the observed and predicted values are similar, the Nash-Sutcliffe coefficient is used (Martinec and Rango, 1989). This goodness of fit measures average observation against the predicted and actual observations for the entire plume and can also be expressed as the coefficient of determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(C_{obs_i} - C_{pred_i})^2}{\sum_{i=1}^{n}(C_{obs_i} - \overline{C})^2} \qquad [8]$$

where $\overline{C}$ is the average observed concentration and n is the number of observations. If $R^2 = 1$, then all variation in the dependant variable is explained by the independent variable and there will be no scatter about the regression line. Another measure of the quality of the estimation criteria is the standard error (SE) which represents the variability in the measurement. It is calculated by the following equation:

$$SE = \sqrt{\frac{(\sum y\ ) - a \cdot (\sum y) - b \cdot \sum xy}{n-2}} \qquad [9]$$

It is noted that the smaller the standard error then the less significant the uncertainty and variability in the regression equation. However, it is important to consider all statistical variables in the determination of the best fit for the data as the slope and intercept points

can reveal any bias in the data. Figures 5.8 to 5.11 represent the regression estimations for the CORMIX iterations against the observed data from Trial 1. The results are summarized in Table 5.3.

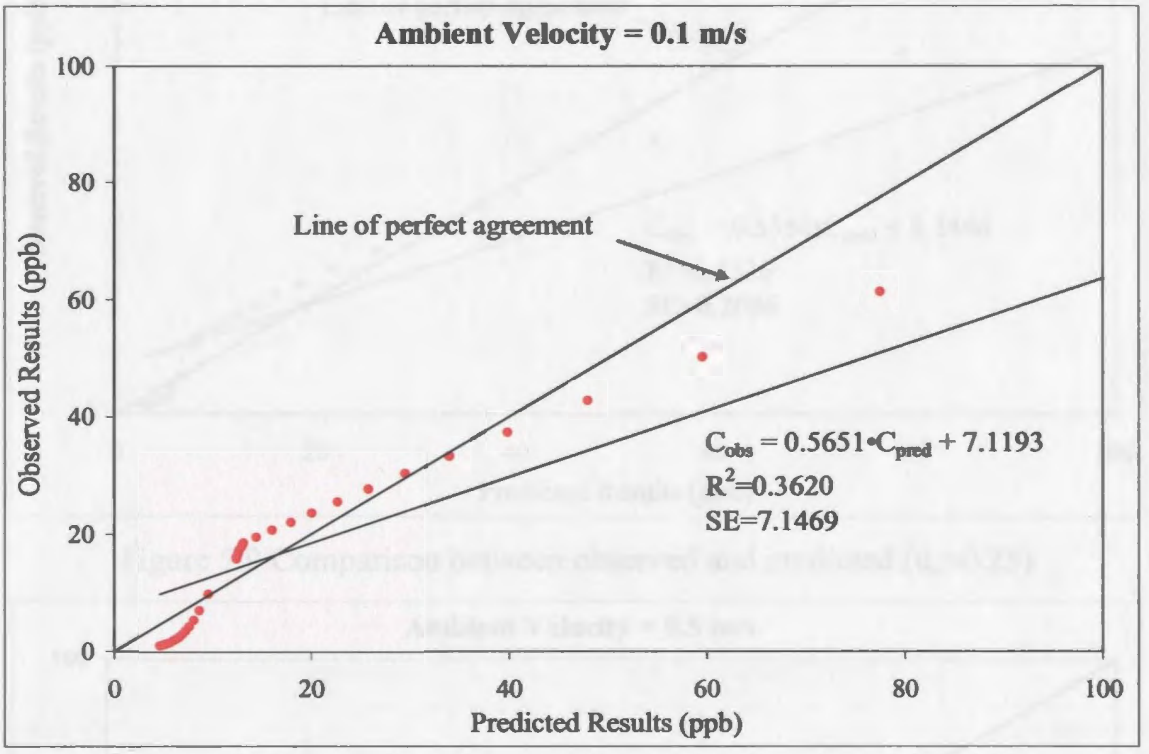

Figure 5.8 Comparison between observed and predicted (u_a=0.1)

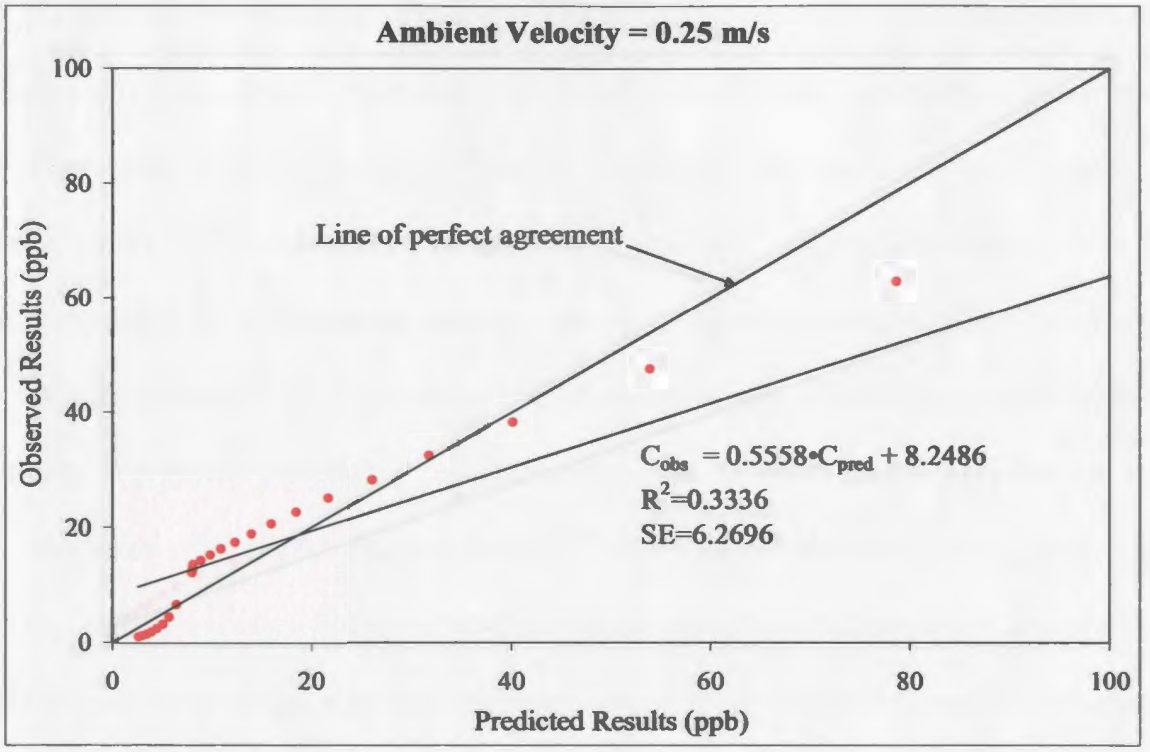

Figure 5.9 Comparison between observed and predicted (u_a=0.25)

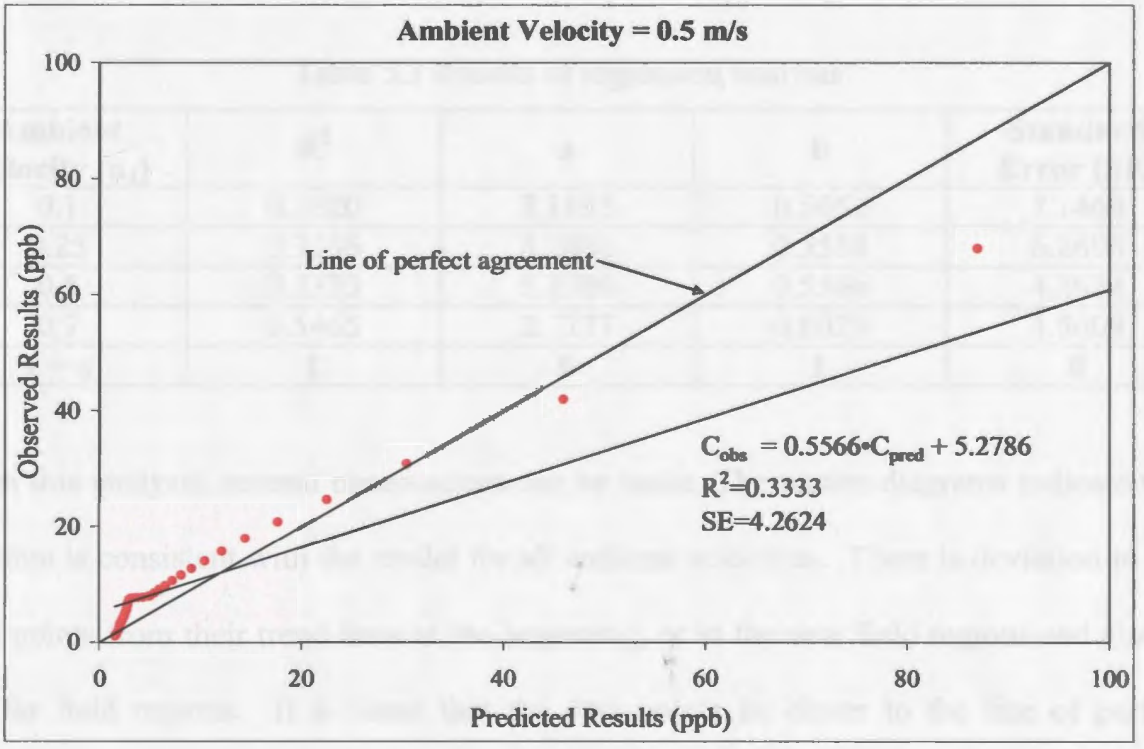

Figure 5.10 Comparison between observed and predicted (u_a=0.5)

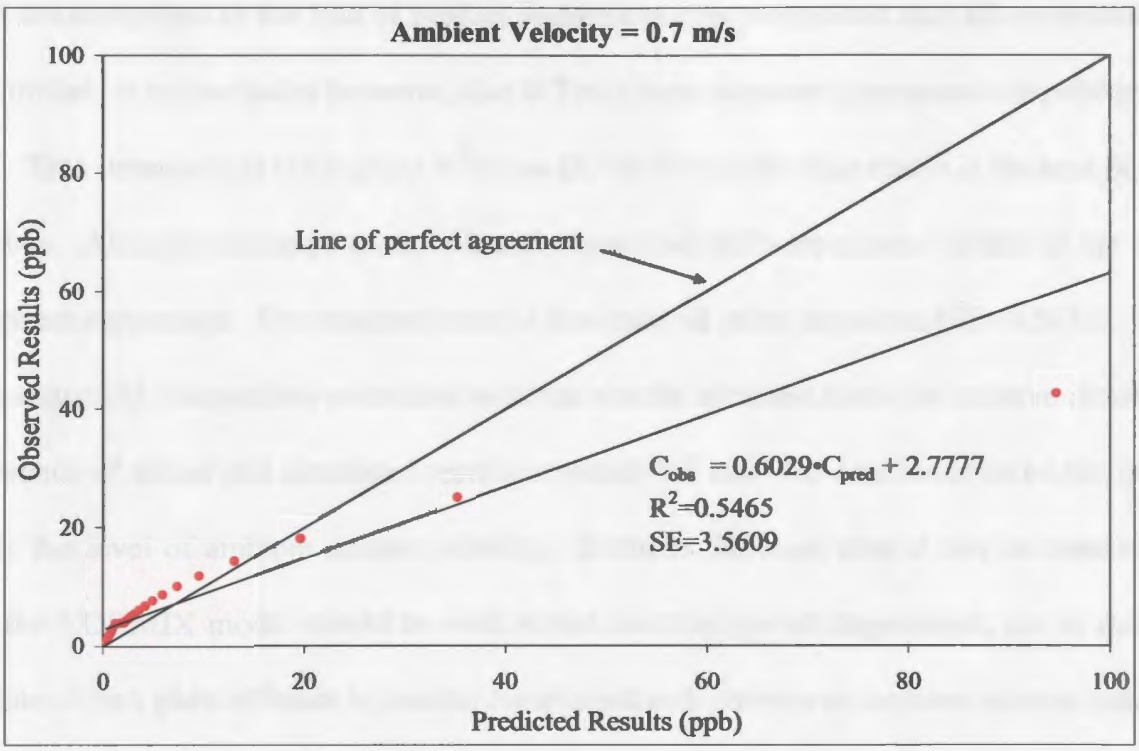

Figure 5.11 Comparison between observed and predicted (u_a=0.7)

Table 5.3 Results of regression analysis

Ambient Velocity (u_a)	R^2	a	b	Standard Error (SE)
0.1	0.3620	7.1193	0.5651	7.1469
0.25	0.3336	8.2486	0.5558	6.2696
0.5	0.3333	5.2786	0.5566	4.2624
0.7	0.5465	2.7777	0.6029	3.5609
y = x	**1**	**0**	**1**	**0**

From this analysis, several observations can be made. The scatter diagrams indicate that the data is consistent with the model for all ambient velocities. There is deviation in the data points from their trend lines at the beginning, or in the near field regions and also at the far field regions. It is noted that the data points lie closer to the line of perfect agreement than the estimated regression line in the near field region. When the trend

lines are compared to the line of perfect agreement it is recognized that all observations are similar. It is concluded however, that 0.7 m/s most accurately represents the observed data. This iteration has the highest R^2 value (R^2=0.547) indicating that it is the best fit for the data. Also, the intercept (a=2.778) and slope (b=0.603) are closest to that of the line of perfect agreement. The standard error is less than all other iterations (SE=3.561).

This statistical comparison coincides with the results obtained from the relative absolute difference of actual and simulated results in which 0.7 m/s was concluded to be the most likely the level of ambient current velocity. If this is the case, then it can be concluded that the CORMIX model would be well suited for this type of experiment, i.e. to model the fate of fish plant effluent in coastal Newfoundland. However, ambient current data is required to validate this conclusion since uniform ambient current was assumed for the whole region of prediction in this analysis.

5.4 Summary

Several topics involving effluent plume monitoring were presented in this thesis. Chapter One reviews typical effluent plumes that exist in Newfoundland and Labrador. It was determined that although seafood processing waste may not represent the most harmful waste stream discharged in the Newfoundland coastal environment, it is the largest. Given that there are so many fish plants throughout the province, mainly in small rural communities with isolated bays and harbours, this source of waste can have major implications to rural development. Municipal wastewater, however, should not be overlooked as Atlantic Canada's treatment facilities are limited. There is a wide range of potential components which can be extremely hazardous to the ecosystem and human

health. Produced water represents a substantial and more recent source of wastewater in Newfoundland waters. Since the location of the present oil and gas platforms are 300 km from the coastal zone, this is not an immediate concern to most rural communities but should not be ignored as certain components could be far reaching if not controlled.

There are many oceanographic parameters that can be studied to obtain an assessment of water quality in areas with active effluent plumes. Traditionally, these parameters have been measured by towing sensors or taking samples from the side of a vessel. AUVs have been identified as a scientific platform that can be used to obtain the data in a more efficient manner by obtaining continuous measurements. Another benefit to using this type of platform is the ability to consistently follow a pre-programmed mission which can be used to obtain repeated measurements with more certainty than with a human operator. Physical, chemical and biological sensors can be mounted onto the platform depending on the type of effluent and the purpose of the experiment. A review of various sensors that can be utilized for effluent monitoring on AUVs is presented in Chapter Two.

Mathematical models have been developed to predict the near field behaviour of plumes under steady-state conditions (Mukthasor, 2001; Jirka et al., 1996; Huang et al., 1994). However, to ensure these models are accurate *in situ* measurements of an actual waste field are critical to evaluate these models. Field measurements can be used to compare against predicted values in validation experiments. Regardless, these models require the input of the discharge and ambient conditions which may be difficult to obtain. Validation experiments can be difficult to conduct due to high costs, variability of

discharge flow rate, currents and stratification and the potential size of study area (Carvalho et al., 2002).

In this experiment, a dye tracer and other physical parameters were used to trace the flow of a fish plant's simulated effluent and compare it to a well-established model. However, due to the lack of ambient current data, several iterations were conducted to determine if an appropriate value of the current could be obtained that would yield a satisfactory correlation to the actual data. A buoyant object was placed into the water to estimate the surface currents, but due to surface waves and wind conditions measurements were futile. The ambient conditions were assumed to be steady. Through an iterative process, it was determined that CORMIX limited the range of ambient velocity values that could be utilized due to small effluent flow rate, a known parameter. This limitation reduced the number of possible iterations and configuration schema.

CORMIX was used to predict the concentration of the tracer as it travels away from the source given various input parameters. Predicted concentrations start directly at the outfall location where the concentration is full strength. Data collected from field tests do not contain measurements directly at the source but within roughly 1.5 m of the pipe. This may have resulted in a source of error in the attempt to correlate the data sets. Initial predicted concentrations were input as 500 ppb whereas the highest concentration obtained from the actual data is 31.27 ppb in Trial 1. It may be possible to obtain similar results to predicted models if samples were taken at the discharge point. Therefore, to adjust for this discrepancy the assumed plume line of the actual data did not commence directly at the outfall location but at the area of highest concentration.

Spatial measurements obtained from the GPS yielded data that were approximately 1.5 m apart from each other. It may be difficult to obtain precise representation of field data using traditional sampling methods (i.e. boat-based) that coincides with the accuracy of CORMIX output. This deficiency was overcome by using GIS software to interpolate the data across the entire study area and convert the grid back into points to obtain estimates for areas that were originally data deficient. However, while this method is useful in smoothing the data over the study region, it did result in another potential source of error or uncertainty. As noted during Trial 3, there were several high measurements of RWT that were not incorporated into the interpolated image because there were a limited number of high values in their vicinity. However, spatial analysis methods including interpolation have been proven in scientific literature to be useful in converting the fragmented information into a smooth gradient of data points (Kitsiou and Karydis, 2001).

RWT was added to a freshwater flow from the fish plant because it was not operational; therefore, the actual discharge characteristics will differ from the presented results. Fish plant solid waste in Newfoundland is typically discharged into a barge or receiving vessel below the outfall pipe for collection before being towed to a gurry ground. Wastewater can be discharged in a separate pipe, or as in the case of Aquaforte, along with the solid waste where it spills into the receiving environment. There are no standard outfalls because there are no direct regulations concerning pipe configuration in the province. An experimental design reflecting this situation is difficult to recreate while a site is not

operational. In this case, the apparatus was designed to emulate the CORMIX schema and potential offshore discharges.

Measurements were obtained and analyzed for the following parameters: temperature, conductivity, dissolved oxygen and rhodamine WT. Since no waste was being discharged at the time of the experiment, the parameter which yielded the best overall results in obtaining a plume was rhodamine WT because it represents a chemical component with a very small background level and it was much easier to recognize areas of high concentration compared to background conditions.

A correlation matrix was constructed for all the trials and parameters. Trial 1 yielded typical results for a study of this nature in that there were strong relationships between temperature, salinity and dissolved oxygen. Temperature and salinity were positively correlated while both parameters were negatively correlated with dissolved oxygen. There was no relationship between RWT and any parameters suggesting that the RWT either did not represent the plume, or the plume was not significantly different from the ambient physical conditions. The profiles of Trial 1 (Figures 4.3, 4.5, 4.7, and 4.9) indicate that the plume trends for temperature, salinity and dissolved oxygen are all similar but they are approximately 45° from the RWT plume.

The RWT plume for Trial 1 was compared to a predictive discharge model. Current values could not be obtained so several estimated ambient current velocities were used to achieve CORMIX results. Using these iterations, a close approximation to the actual ambient current velocity prevailing at the time of the test was achieved. Real ambient current data to confirm this assumption is required.

Chapter 6 Conclusion and Recommendations

6.1 Conclusion

Seafood processing effluent was found to be the largest waste stream originating from coastal Newfoundland. To provide an assessment of the extent of the waste field surrounding a fish plant, sensors were selected and used to map a simulated effluent plume at a fish plant in Aquaforte, NL.

Physical parameters measured in these tests are characteristic for coastal regions during late fall, i.e. lower temperature and salinity values and higher levels of dissolved oxygen saturation. Rhodamine WT was measured and compared to CORMIX simulations given a series of ambient conditions. The predicted values clearly show the regions of near field and far field components of the discharge plume. Due to uncertainty in the data, there is no clear indication of the near and far field components of the actual plume. The plume concentration data recorded show a decaying exponential trend over the same overall range as the CORMIX plume simulations. The regions covered by the data measure the near-field, far-field and transitional regions of the plume. The far field predictions from CORMIX fit the plume concentration more closely in an absolute value sense than the near field predictions but actual concentrations in this region are low, less than 5 ppb so percentage differences are high. The plume concentration data shows variation in the predicted and observed data of up to ±3 ppb in the near field and reducing to about ±1 ppb in the far field for the closest estimation to the actual results. Within the

uncertainty bands of the data, the CORMIX predictions were found to represent the data for nearly all current values assumed (from 0.1 to 0.7 m/s).

This conclusion was verified using a regression analysis. Iterations were plotted against the curve fit for the observed data at the same location resulting in a scatter plot. The trend line was compared to a line of perfect agreement. It was found that 0.7 m/s yielded the best regression line as it was more closely associated with the line of perfect agreement and had the highest Nash-Sutcliffe coefficient ($R^2 = 0.5465$).

It was determined that fish plant effluent can be simulated given accurate background information by comparing the field data to the CORMIX model. However, if this information is not available assumptions and estimates can be made, but it will inevitably increase the amount of uncertainty in the estimate and decrease the power of the test. Models require validation to determine if they can be used for their specific purpose. It is particularly important if little information exists about the waste stream such as fish plant effluent in the province of Newfoundland and Labrador.

Effluent plumes can be very diverse resulting in numerous impacts on the receiving environment, depending on the composition and quantity. It is critical to understand what is being deposited into the coastal zone in order to properly assess any potential meditative measures that could be imposed to improve the conditions. It is also important to test and validate predictive models such as CORMIX to ensure they are used properly and are accurate. This work identified a waste stream that has been poorly studied in terms of the fate and effects in the province of Newfoundland and Labrador. A test was conducted to determine if a discharge model could be used to map the plume. It

was determined that for the simulated fish plant effluent used in this experiment it can be a useful tool. Fish plant effluents are not well studied and more focus should be given to ensure all necessary measures are in place to maintain the long-term viability of Newfoundland and Labrador's coastal environment.

6.2 Recommendations

Following the completion of any experiment there are inevitably several recommendations that can be made to improve the test. This work was no exception. Recommendations include the following:

- This experiment utilized simulated fish plant effluent, i.e. the typical source of water with a similar flow rate mixed with RWT. True effluent would have been preferred; however, due to the seasonal nature of the fishing industry, this was impossible. Future experimentation on real fish plant effluent would be beneficial in determining if there is a change in the dilution patterns as well as in the determination if the other parameters can be used to trace the plume.
- The dissolved oxygen measurements were very high. Particularly, in Trial 2 it appeared that there was noise in the data structure. The sensor was not recalibrated prior to deployment before that session. This could have affected the results in that they may not accurately depict the actual conditions. Therefore, recalibration and checking of the dissolved oxygen sensor should be performed before each deployment.
- Although the package of three sensors was useful in determining the overall water quality of the harbour, other sensor types may also be beneficial such as the

measurement of total suspended solids, one of the major pollutants of fish plant effluent.

- Ambient current data was not obtained at the time of the experiment. This information is needed for the comparison of the field data and the predicted values derived from CORMIX. The estimated values were useful in the determination if the model was relevant to fish plant effluents; if this information was known further analysis could have been conducted.
- Finally, Chapter Two describes the benefits of using AUVs for environmental monitoring. The use of a reliable AUV was preferred for this experiment. Instead, it provided a set of baseline data from future work involving AUVs and fish plants. Future work in this area should be continued as it represents an area of research that has not been well studied in the province.

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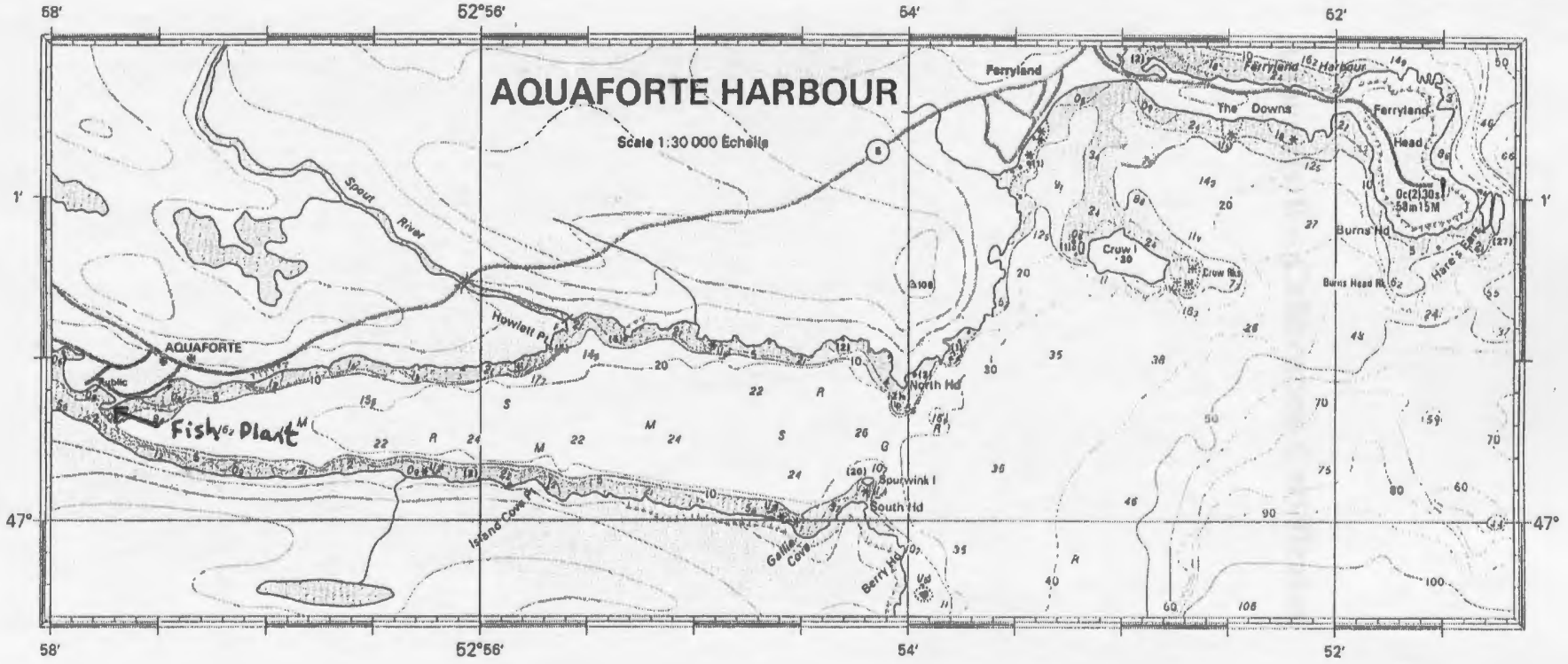
Appendix A – Aquaforte Harbour


AQUAFORTE HARBOUR
Scale 1:30 000 Échelle
58'
52°56'
54'
52'
1'
47°
Ferryland
Ferryland Harbour
The Downs
Ferryland Head
Spout River
Howlett Pt
AQUAFORTE
Public
Fish Plant
North Hd
Spurwink I
South Hd
Island Cove Pt
Gallie Cove
Berry Hd
Crow I
Crow Rks
Burns Hd
Burns Head Rk
Hare's Ears

Appendix B – Calibration Certificates

Micro CTD 7163

Micro C Calibration

Job Information

Date	08-19-2004
Job Number	4257
Customer	Memorial University of Newfoundland

Sensor Information

Manufacturer	AML
Model Number	Type J
Serial Number	124-3
Range	0 to 7 S/m
Channel	3
Calibrated By	JR
Standards	Autosal/Hart/T2128

Calibration Data

Raw	Nref	Nte	C Ratio	Real
26888	0	162	0.750025	0.750041
30837	0	150	0.861981	0.861980
35111	0	135	0.983160	0.983043
39343	0	120	1.102648	1.102815
43709	0	105	1.226310	1.226292
48375	0	92	1.358316	1.358234
54694	0	76	1.536858	1.536892

Coefficients

A = -1.241240E-02
B = 4.042094E-06
C = -1.958428E-08
D = 2.591705E-11
E = 2.832684E-05
F = -6.698583E-10
G = 1.101161E-11
H = -3.763823E-14

=A+B*Nte+C*Nte^2+D*Nte^3+(E+F*Nte+G*Nte^2+H*Nte^2)*Raw

RMS = 0.0001

Applied Microsystems Ltd.
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Canada & USA: 800-663-8721
Email: info@AppliedMicrosystems.com Web: http://www.aml.bc.ca

Micro CTD 7163

Micro T Calibration

Job Information

Date	08-18-2004
Job Number	4257
Customer	Memorial University of Newfoundland

Sensor Information

Manufacturer	Thermometrics/AML
Model Number	Type K
Serial Number	154-2
Range	-2 to +32 Deg C
Channel	2
Calibrated By	JR
Standards	Hart/T2128

Calibration Data

Raw	Standard
8048	-1.406
10229	0.246
13700	2.770
17145	5.199
20811	7.703
24703	10.303
27998	12.472
32085	15.141
35885	17.619
39472	19.972
43353	22.549
46955	24.985
51256	27.977
56161	31.535

Coefficients

A = -7.998308E+00
B = 8.813541E-04
C = -9.022883E-09
D = 1.785570E-13
E = -2.186333E-18
F = 1.851806E-23
G = -5.514914E-29

=A+B*Raw+C*Raw^2+D*Raw^3+E*Raw^4+F*Raw^5+G*Raw^6

RMS = 0.0015

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Micro CTD 7163

Fluorometer Calibration

Job Information

Date	09-08-2004
Job Number	4257
Customer	Memorial University of Newfoundland

Sensor Information

Manufacturer	Turner Designs
Model Number	Cyclopse-7 No. 2100-000
Serial Number	2100089
Range	0 to 500 ug/L Chl
Channel	4
Calibrated By	JR
Standards	Voltmeter

Calibration Data

Raw	Standard
15	0.002
10918	1.012
21601	2.002
32387	3.002
43191	4.004
53991	5.005

Coefficients

A = 9.860764E-05
B = 9.269852E-05

=A+B*Raw

RMS = 0.0001

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TURNER DESIGNS
845 W. Maude Avenue • Sunnyvale, CA 94085
(408) 749-0994 • FAX (408) 749-0998
www.turnerdesigns.com • Toll free 1-877-316-8049

Specification Certificate

Product: CYCLOPS-7 Submersible Fluorometer, PN 2100-000

Application: Rhodamine or Fluorescein Dye
Note: Rhodamine versions are stamped with the Letter "R" on the connector. Fluorescein versions are stamped with the Letter "F" on the connector.

This certificate confirms that the CYCLOPS-7 with **Serial Number:** 2100094
has passed all manufacturing performance testing and meets the specifications detailed below.

For operating instructions, please refer to the CYCLOPS-7 User's Manual contained on the CD disk that is included with the unit or can be viewed at the following web link:
http://www.turnerdesigns.com/t2/doc/manuals/main.html

Measurement Parameter	X 1 Gain	X 10 Gain	X 100 Gain
Blank Solution – Deionized water, millivolt output	0 to 35 mV	0 to 75 mV	0 to 150 mV
Standard deviation in Deionized water	1 mV	2 mV	7 mV
Maximum Concentration value (+/- 5%)	1000 ug/L	100 ug L	10 ug/L
Minimum Concentration Detection (ug/L = PPB)	0.36 ug L	0.12 ug L	0.04 ug L
Gain Factor Spec.	X 1	X 10, +/- 5%	X100, +/- 5%

Appendix C – Summary Statistics

Summary Statistics - Days		Depth (m)	Conductivity (mS/cm)	Temperature (deg C)	Fluorometer (ppb)	Dissolved Oxygen (%sat)	Salinity (PSU)	Density	Sound Velocity
Trial 1 - October 22, 2004	Count	5145	5145	5145	5145	5145	5145	5145	5145
	Mean	0.846	28.852	9.525	1.924	110.729	26.078	20.071	1477.242
	Mode	1.000	30.825	9.579	1.160	110.000	27.687	21.556	1480.000
	Minimum	0.316	21.715	9.257	0.800	103.000	19.204	14.744	1468.040
	Maximum	1.255	31.287	9.632	31.270	119.300	28.453	21.913	1480.420
	Range Difference	0.938	9.572	0.375	30.470	16.300	9.249	7.169	12.380
	Standard Deviation	0.301	2.232	0.070	2.303	3.822	2.168	1.681	2.887
	95% Confidence Interval	0.008	0.061	0.002	0.063	0.104	0.059	0.046	0.079
Trial 2 - October 26, 2004: Morning	Count	5653	5653	5653	5653	5653	5653	5653	5653
	Mean	0.468	10.862	8.705	2.218	138.029	9.227	7.036	1453.510
	Mode	0.408	9.990	8.705	1.930	130.900	8.234	6.201	1452.460
	Minimum	0.173	6.404	8.632	1.530	102.300	5.227	3.918	1448.300
	Maximum	0.765	18.224	8.904	15.120	187.100	16.040	12.329	1462.640
	Range Difference	0.592	11.820	0.272	13.590	84.800	10.813	8.411	14.340
	Standard Deviation	0.149	2.268	0.026	0.947	10.877	2.076	1.620	2.575
	95% Confidence Interval	0.004	0.059	0.001	0.025	0.284	0.054	0.042	0.067
Trial 3 - October 26, 2004: Afternoon	Count	5216	5216	5216	5216	5216	5216	5216	5216
	Mean	0.485	10.070	8.836	3.282	141.902	8.482	6.442	1453.115
	Mode	0.673	7.945	8.790	2.140	146.300	6.747	4.942	1450.770
	Minimum	0.194	5.849	8.747	1.520	108.200	4.729	3.519	1448.160
	Maximum	0.928	19.672	9.013	31.450	179.700	17.382	13.362	1464.700
	Range Difference	0.734	13.823	0.266	29.930	71.500	12.653	9.843	16.540
	Standard Deviation	0.190	2.830	0.051	2.435	7.476	2.571	2.002	3.351
	95% Confidence Interval	0.005	0.077	0.001	0.066	0.203	0.070	0.054	0.091
Trial 4 - October 27, 2005	Count	1097	1097	1097	1097	1097	1097	1097	1097
	Mean	0.305	8.692	8.720	1.930	144.544	7.240	5.483	1451.127
	Mode	0.306	8.730	8.717	1.930	145.800	7.306	5.514	1451.15
	Minimum	0.235	7.217	8.658	1.870	136.600	5.925	4.454	1449.580
	Maximum	0.377	9.895	8.791	2.020	150.100	8.330	6.338	1452.330
	Range Difference	0.143	2.678	0.133	0.150	13.500	2.405	1.884	2.750
	Standard Deviation	0.020	0.502	0.031	0.019	2.234	0.453	0.356	0.503
	95% Confidence Interval	0.001	0.030	0.002	0.001	0.132	0.027	0.021	0.030
Overall	Count	17111	17111	17111	17111	17111	17111	17111	17111
	Mean	0.576	15.891	8.992	2.435	131.418	13.939	10.675	1460.373
	Mode	0.408	30.825	8.705	1.930	146.300	6.747	5.240	1450.770
	Minimum	0.173	5.849	8.632	0.800	102.300	4.729	3.519	1448.160
	Maximum	1.255	31.287	9.632	31.450	187.100	28.453	21.913	1480.420
	Range Difference	1.081	25.438	1.000	30.650	84.800	23.724	18.394	32.260
	Standard Deviation	0.280	8.842	0.357	2.007	15.765	8.275	6.408	11.437
	95% Confidence Interval	0.004	0.132	0.005	0.030	0.236	0.124	0.096	0.171

Summary Statistics - Casts in Trial 1		Depth (m)	Conductivity (mS/cm)	Temperature (deg C)	Fluorometer (ppb)	Dissolved Oxygen (%sat)	Salinity (PSU)	Density	Sound Velocity
Cast 1 (16:43)	Count	995	995	995	995	995	995	995	995
	Mean	0.995	30.600	9.571	3.239	113.209	27.782	21.393	1479.489
	Mode	1.000	30.604	9.579	0.880	112.900	27.687	21.444	1479.120
	Minimum	0.734	30.107	9.493	0.830	109.700	27.283	21.002	1478.850
	Maximum	1.061	31.282	9.626	31.270	117.900	28.440	21.901	1480.420
	Range Difference	0.326	1.175	0.133	30.440	8.200	1.157	0.899	1.570
	Standard Deviation	0.018	0.237	0.020	3.989	1.236	0.230	0.178	0.321
	95% Confidence Interval	0.001	0.015	0.001	0.248	0.077	0.014	0.011	0.020
Cast 2 (22:40)	Count	1350	1350	1350	1350	1350	1350	1350	1350
	Mean	0.411	25.857	9.438	1.417	114.001	23.169	17.815	1473.371
	Mode	0.418	30.604	9.420	1.470	113.100	27.687	21.444	1479.120
	Minimum	0.316	21.715	9.257	0.830	105.000	19.204	14.744	1468.040
	Maximum	1.061	31.282	9.626	31.270	119.300	28.440	21.901	1480.420
	Range Difference	0.745	9.567	0.369	30.440	14.300	9.236	7.157	12.380
	Standard Deviation	0.290	2.619	0.075	2.753	2.798	2.545	1.974	3.370
	95% Confidence Interval	0.015	0.140	0.004	0.147	0.149	0.136	0.105	0.180
Cast 3 (13:05)	Count	775	775	775	775	775	775	775	775
	Mean	0.691	27.654	9.479	1.676	111.456	24.914	19.169	1475.649
	Mode	0.694	27.755	9.489	1.140	112.300	25.083	19.073	1475.700
	Minimum	0.316	21.715	9.257	0.830	105.000	19.204	14.744	1468.040
	Maximum	0.755	29.412	9.541	8.840	115.200	26.633	20.503	1477.890
	Range Difference	0.439	7.697	0.284	8.010	10.200	7.429	5.759	9.850
	Standard Deviation	0.014	0.736	0.028	1.019	1.488	0.714	0.553	0.953
	95% Confidence Interval	0.001	0.052	0.002	0.072	0.105	0.050	0.039	0.067
Cast 4 (10:44)	Count	261	261	261	261	261	261	261	261
	Mean	1.001	30.307	9.564	2.390	109.266	27.495	21.171	1479.112
	Mode	1.000	30.356	9.589	1.030	109.900	27.653	21.336	1479.090
	Minimum	0.979	29.277	9.476	0.890	106.300	26.487	20.389	1477.780
	Maximum	1.030	30.845	9.624	15.660	110.900	28.001	21.559	1479.880
	Range Difference	0.051	1.568	0.148	14.770	4.600	1.514	1.170	2.100
	Standard Deviation	0.010	0.241	0.035	2.623	1.158	0.241	0.188	0.315
	95% Confidence Interval	0.001	0.029	0.004	0.318	0.140	0.029	0.023	0.038
Cast 5 (29:38)	Count	1764	1764	1764	1764	1764	1764	1764	1764
	Mean	1.139	30.470	9.581	1.610	106.723	27.645	21.285	1479.361
	Mode	1.193	30.786	9.573	0.950	105.700	28.116	21.556	1480.050
	Minimum	0.796	28.973	9.478	0.800	103.000	26.175	20.144	1477.430
	Maximum	1.255	31.287	9.632	18.670	110.900	28.453	21.913	1480.400
	Range Difference	0.459	2.314	0.154	17.870	7.900	2.278	1.769	2.970
	Standard Deviation	0.074	0.571	0.022	1.918	1.721	0.564	0.438	0.726
	95% Confidence Interval	0.003	0.027	0.001	0.090	0.080	0.026	0.020	0.034

Summary Statistics - Casts in Trial 2		Depth (m)	Conductivity (mS/cm)	Temperature (deg C)	Fluorometer (ppb)	Dissolved Oxygen (%sat)	Salinity (PSU)	Density	Sound Velocity
Cast 6 (33:31)	Count	2010	2010	2010	2010	2010	2010	2010	2010
	Mean	0.659	13.577	8.702	2.487	132.563	11.720	8.983	1456.564
	Mode	0.653	13.095	8.676	1.740	130.900	11.237	8.610	1456.850
	Minimum	0.439	11.252	8.650	1.530	107.300	9.571	7.309	1453.830
	Maximum	0.765	18.224	8.904	15.120	159.100	16.040	12.329	1462.640
	Range Difference	0.326	6.972	0.254	13.590	51.800	6.469	5.020	8.810
	Standard Deviation	0.031	0.802	0.030	1.535	7.450	0.742	0.577	1.009
	95% Confidence Interval	0.001	0.035	0.001	0.067	0.326	0.032	0.025	0.044
Cast 7 (33:46)	Count	2023	2023	2023	2023	2023	2023	2023	2023
	Mean	0.404	9.616	8.694	2.081	140.846	8.081	6.143	1452.061
	Mode	0.408	9.716	8.700	1.930	147.200	8.155	6.592	1451.910
	Minimum	0.337	6.404	8.632	1.770	109.600	5.227	3.918	1448.300
	Maximum	0.530	12.621	8.757	4.380	178.200	10.820	8.277	1455.560
	Range Difference	0.194	6.217	0.125	2.610	68.600	5.593	4.359	7.260
	Standard Deviation	0.020	1.192	0.022	0.195	10.964	1.069	0.833	1.389
	95% Confidence Interval	0.001	0.052	0.001	0.009	0.478	0.047	0.036	0.061
Cast 8 (27:05)	Count	1621	1621	1621	1621	1621	1621	1621	1621
	Mean	0.311	9.052	8.721	2.057	141.289	7.565	5.737	1451.532
	Mode	0.306	9.865	8.729	2.010	145.400	8.295	6.201	1452.460
	Minimum	0.173	6.701	8.671	1.860	102.300	5.480	4.111	1448.790
	Maximum	0.428	11.164	8.755	3.330	187.100	9.475	7.227	1453.940
	Range Difference	0.255	4.463	0.084	1.470	84.800	3.995	3.116	5.150
	Standard Deviation	0.021	1.008	0.016	0.144	11.673	0.901	0.703	1.160
	95% Confidence Interval	0.001	0.049	0.001	0.007	0.568	0.044	0.034	0.056

Summary Statistics - Casts in Trial 3		Depth (m)	Conductivity (mS/cm)	Temperature (deg C)	Fluorometer (ppb)	Dissolved Oxygen (%sat)	Salinity (PSU)	Density	Sound Velocity
Cast 9 (10:16)	Count	1325	1325	1325	1325	1325	1325	1325	1325
	Mean	0.416	8.535	8.792	2.802	141.138	7.092	5.361	1451.236
	Mode	0.398	8.342	8.790	2.140	144.700	6.574	5.091	1450.990
	Minimum	0.357	6.500	8.769	1.520	113.000	5.291	3.956	1448.940
	Maximum	0.928	17.428	8.945	13.240	179.500	15.261	11.719	1461.860
	Range Difference	0.571	10.928	0.176	11.720	66.500	9.970	7.763	12.920
	Standard Deviation	0.094	1.518	0.025	1.470	7.253	1.382	1.077	1.789
	95% Confidence Interval	0.005	0.082	0.001	0.079	0.391	0.074	0.058	0.096
Cast 10 (17:45)	Count	1053	1053	1053	1053	1053	1053	1053	1053
	Mean	0.671	9.793	8.825	2.794	142.491	8.228	6.246	1452.763
	Mode	0.673	9.985	8.810	1.950	144.000	7.619	5.713	1448.580
	Minimum	0.602	5.849	8.747	1.650	108.300	4.729	3.519	1448.160
	Maximum	0.745	16.979	8.963	8.890	179.700	14.828	11.379	1461.380
	Range Difference	0.143	11.130	0.216	7.240	71.400	10.099	7.860	13.220
	Standard Deviation	0.022	2.447	0.042	1.295	7.650	2.209	1.720	2.875
	95% Confidence Interval	0.001	0.148	0.003	0.078	0.462	0.133	0.104	0.174
Cast 11 (25:14)	Count	1481	1481	1481	1481	1481	1481	1481	1481
	Mean	0.247	8.189	8.817	4.727	146.205	6.772	5.109	1450.941
	Mode	0.235	7.932	8.820	2.270	146.800	6.556	4.942	1450.660
	Minimum	0.194	6.647	8.781	1.820	121.400	5.417	4.053	1449.130
	Maximum	0.622	15.308	8.927	31.450	165.700	13.262	10.162	1459.340
	Range Difference	0.428	8.661	0.146	29.630	44.300	7.845	6.109	10.210
	Standard Deviation	0.038	0.713	0.015	3.741	2.181	0.637	0.496	0.836
	95% Confidence Interval	0.002	0.036	0.001	0.191	0.111	0 032	0.025	0.043
Cast 12 (22:48)	Count	1357	1357	1357	1357	1357	1357	1357	1357
	Mean	0.669	13.837	8.906	2.553	137.494	11.902	9.104	1457.594
	Mode	0.683	15.214	8.921	1.960	139.100	10.247	9.189	1457.490
	Minimum	0.418	9.144	8.851	1.600	108.200	7.615	5.766	1452.130
	Maximum	0.755	19.672	9.013	7.020	174.900	17.382	13.362	1464.700
	Range Difference	0.337	10.528	0.162	5.420	66.700	9.767	7.596	12.570
	Standard Deviation	0.032	1.709	0.025	0.945	8.515	1.580	1.229	2.027
	95% Confidence Interval	0.002	0.091	0.001	0.050	0.453	0.084	0.065	0.108

Appendix D – CORMIX Prediction Results

```
CORMIX1 PREDICTION FILE:
111111111111111111111111111111111111111111111111111111111111111111111111111111
                      CORNELL MIXING ZONE EXPERT SYSTEM
             Subsystem CORMIX1:  Submerged Single Port Discharges
 CORMIX-GI Version 4.1GT
-------------------------------------------------------------------------------
-------------------------------------------------------------------------------
CASE DESCRIPTION
 Site name/label:   Aquaforte
 Design case:       October 22
 FILE NAME:         C:\...top\Sara's Important Stuff\Cormix\Oct22\Oct22.prd
 Time stamp:        Sat Mar 26 10:45:59 2005

ENVIRONMENT PARAMETERS (metric units)
 Unbounded section
 HA    =      3.50  HD    =      2.64
 UA    =     0.100  F     =     0.032 USTAR =0.6355E-02
 UW    =     5.556  UWSTAR=0.6623E-02
 Uniform density environment
 STRCND=  U         RHOAM = 1020.0630

DISCHARGE PARAMETERS (metric units)
 BANK  =  LEFT      DISTB =     25.00
 D0    =     0.051 A0    =     0.002 H0    =      0.88
 THETA =      0.00 SIGMA =      0.00
 U0    =     7.398 Q0    =     0.015       =0.1500E-01
 RHO0  =  999.7422  DRHO0 =0.2032E+02  GP0   =0.1954E+00
 C0    = 0.4980E+03 CUNITS=  ppb
 IPOLL =  1         KS    =0.0000E+00  KD    =0.0000E+00

FLUX VARIABLES (metric units)
 Q0    =0.1500E-01  M0    =0.1110E+00  J0    =0.2930E-02  SIGNJ0=      1.0
 Associated length scales (meters)
 LQ    =     0.05  LM    =     3.55  Lm    =     3.33  Lb    =     2.93
                                     Lmp   =  99999.00  Lbp   =  99999.00

NON-DIMENSIONAL PARAMETERS
 FR0   =     74.25  R     =     73.98

FLOW CLASSIFICATION
 1111111111111111111111111111111111111111
 1  Flow class (CORMIX1)      =    H4-0   1
 1  Applicable layer depth HS =     2.64  1
 1111111111111111111111111111111111111111

MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS
 C0    = 0.5000E+03 CUNITS=  ppb
 NTOX  =  0
 NSTD  =  0
 REGMZ =  0
 XINT  =    175.00  XMAX  =    175.00

X-Y-Z COORDINATE SYSTEM:
    ORIGIN is located at the bottom and below the center of the port:
        25.00 m  from the LEFT  bank/shore.
    X-axis points downstream, Y-axis points to left, Z-axis points upward.
NSTEP = 15 display intervals per module
```

```
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN MOD101: DISCHARGE MODULE

       X        Y        Z        S        C        B
    0.00     0.00     0.88      1.0 0.500E+03    0.03

END OF MOD101: DISCHARGE MODULE
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

 Jet/plume transition motion in weak crossflow.

 Zone of flow establishment:              THETAE=      0.00  SIGMAE=      0.00
  LE    =      0.25  XE    =      0.25  YE    =      0.00  ZE    =      0.88

 Profile definitions:
   B = Gaussian 1/e (37%) half-width, normal to trajectory
   S = hydrodynamic centerline dilution
   C = centerline concentration (includes reaction effects, if any)

       X        Y        Z        S        C        B
    0.00     0.00     0.88      1.0 0.500E+03    0.03
    0.25     0.00     0.88      1.0 0.498E+03    0.03
    0.73     0.00     0.88      2.7 0.187E+03    0.08
    1.23     0.00     0.89      4.5 0.110E+03    0.13
    1.73     0.00     0.90      6.4 0.775E+02    0.18
    2.23     0.00     0.92      8.4 0.595E+02    0.23
    2.73     0.00     0.95     10.4 0.479E+02    0.28
    3.23     0.00     0.99     12.5 0.398E+02    0.32
    3.73     0.00     1.04     14.7 0.339E+02    0.37
    4.20     0.00     1.10     16.9 0.294E+02    0.42
    4.70     0.00     1.17     19.4 0.257E+02    0.47
    5.19     0.00     1.26     22.0 0.226E+02    0.52
    5.69     0.00     1.36     24.8 0.200E+02    0.57
    6.18     0.00     1.47     27.9 0.179E+02    0.62
    6.66     0.00     1.59     31.1 0.160E+02    0.67
    7.15     0.00     1.72     34.6 0.144E+02    0.73
    7.60     0.00     1.85     38.1 0.131E+02    0.78
 Cumulative travel time =          11. sec

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

  Control volume inflow:
       X        Y        Z        S        C        B
    7.60     0.00     1.85     38.1 0.131E+02    0.78

 Profile definitions:
   BV = Gaussian 1/e (37%) vertical thickness
   BH = Gaussian 1/e (37%) horizontal half-width, normal to trajectory
   ZU = upper plume boundary (Z-coordinate)
   ZL = lower plume boundary (Z-coordinate)
   S = hydrodynamic centerline dilution
```

C = centerline concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
6.82	0.00	2.64	38.1	0.131E+02	0.00	0.00	2.64	2.64
7.06	0.00	2.64	38.1	0.131E+02	0.66	0.33	2.64	1.98
7.29	0.00	2.64	38.1	0.131E+02	0.78	0.47	2.64	1.86
7.53	0.00	2.64	38.1	0.131E+02	0.86	0.57	2.64	1.78
7.76	0.00	2.64	38.2	0.130E+02	0.91	0.66	2.64	1.73
7.99	0.00	2.64	38.6	0.129E+02	0.96	0.74	2.64	1.68
8.23	0.00	2.64	39.1	0.127E+02	0.99	0.81	2.64	1.65
8.46	0.00	2.64	39.6	0.126E+02	1.02	0.87	2.64	1.62
8.69	0.00	2.64	40.0	0.125E+02	1.03	0.93	2.64	1.61
8.93	0.00	2.64	40.2	0.124E+02	1.04	0.99	2.64	1.60
9.16	0.00	2.64	40.3	0.124E+02	1.04	1.04	2.64	1.60

Cumulative travel time = 16. sec

END OF MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

BEGIN MOD155: WEAKLY DEFLECTED SURFACE/BOTTOM PLUME

SURFACE/BOTTOM PLUME into a co-flow (or counter-flow)

This flow region is INSIGNIFICANT in spatial extent and will be by-passed.

END OF MOD155: WEAKLY DEFLECTED SURFACE/BOTTOM PLUME

BEGIN MOD156: STRONGLY DEFLECTED SURFACE/BOTTOM PLUME

SPECIAL CO-FLOWING, COUNTER-FLOWING OR VERTICAL DISCHARGE CASE:
THIS FLOW REGION DOES NOT OCCUR.

END OF MOD156: STRONGLY DEFLECTED SURFACE/BOTTOM PLUME

** End of NEAR-FIELD REGION (NFR) **

The initial plume WIDTH values in the next far-field module will be
CORRECTED by a factor 1.66 to conserve the mass flux in the far-field!
The correction factor is quite large because of the small ambient velocity
relative to the strong mixing characteristics of the discharge!
This indicates localized RECIRCULATION REGIONS and internal hydraulic JUMPS.

BEGIN MOD141: BUOYANT AMBIENT SPREADING

Profile definitions:
BV = top-hat thickness, measured vertically
BH = top-hat half-width, measured horizontally in Y-direction
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic average (bulk) dilution
C = average (bulk) concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
9.16	0.00	2.64	40.3	0.124E+02	1.74	1.74	2.64	0.90
15.62	0.00	2.64	52.1	0.956E+01	0.81	4.82	2.64	1.83

22.08	0.00	2.64	57.7	0.864E+01	0.61	7.08	2.64	2.03
28.55	0.00	2.64	61.8	0.806E+01	0.51	9.02	2.64	2.13
35.01	0.00	2.64	65.3	0.762E+01	0.45	10.77	2.64	2.19
41.47	0.00	2.64	68.7	0.725E+01	0.42	12.38	2.64	2.22
47.93	0.00	2.64	72.0	0.692E+01	0.39	13.89	2.64	2.25
54.39	0.00	2.64	75.4	0.661E+01	0.37	15.32	2.64	2.27
60.85	0.00	2.64	78.9	0.631E+01	0.35	16.68	2.64	2.29
67.32	0.00	2.64	82.7	0.602E+01	0.34	17.99	2.64	2.30
73.78	0.00	2.64	86.7	0.574E+01	0.34	19.25	2.64	2.30
80.24	0.00	2.64	91.0	0.547E+01	0.33	20.47	2.64	2.31
86.70	0.00	2.64	95.7	0.521E+01	0.33	21.65	2.64	2.31
93.16	0.00	2.64	100.6	0.495E+01	0.33	22.80	2.64	2.31
99.62	0.00	2.64	105.9	0.470E+01	0.33	23.91	2.64	2.31
106.09	0.00	2.64	111.6	0.446E+01	0.33	25.01	2.64	2.31

Cumulative travel time = 985. sec

Plume is ATTACHED to LEFT bank/shore.
Plume width is now determined from LEFT bank/shore.

Plume Stage 2 (bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
106.09	25.00	2.64	111.6	0.446E+01	0.33	50.01	2.64	2.31
110.68	25.00	2.64	115.3	0.432E+01	0.34	50.76	2.64	2.30
115.27	25.00	2.64	119.2	0.418E+01	0.35	51.50	2.64	2.29
119.87	25.00	2.64	123.2	0.404E+01	0.35	52.24	2.64	2.29
124.46	25.00	2.64	127.3	0.391E+01	0.36	52.97	2.64	2.28
129.06	25.00	2.64	131.5	0.379E+01	0.37	53.70	2.64	2.27
133.65	25.00	2.64	135.8	0.367E+01	0.37	54.42	2.64	2.27
138.25	25.00	2.64	140.2	0.355E+01	0.38	55.14	2.64	2.26
142.84	25.00	2.64	144.8	0.344E+01	0.39	55.85	2.64	2.25
147.43	25.00	2.64	149.4	0.333E+01	0.40	56.56	2.64	2.24
152.03	25.00	2.64	154.2	0.323E+01	0.40	57.26	2.64	2.24
156.62	25.00	2.64	159.0	0.313E+01	0.41	57.96	2.64	2.23
161.22	25.00	2.64	164.0	0.304E+01	0.42	58.66	2.64	2.22
165.81	25.00	2.64	169.1	0.295E+01	0.43	59.35	2.64	2.21
170.41	25.00	2.64	174.3	0.286E+01	0.44	60.04	2.64	2.20
175.00	25.00	2.64	179.6	0.277E+01	0.44	60.72	2.64	2.20

Cumulative travel time = 1674. sec

Simulation limit based on maximum specified distance = 175.00 m.
This is the REGION OF INTEREST limitation.

END OF MOD141: BUOYANT AMBIENT SPREADING

CORMIX1: Submerged Single Port Discharges End of Prediction File

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```
CORMIX1 PREDICTION FILE:
1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111
                      CORNELL MIXING ZONE EXPERT SYSTEM
             Subsystem CORMIX1:  Submerged Single Port Discharges
 CORMIX-GI Version 4.1GT
-------------------------------------------------------------------------------
-------------------------------------------------------------------------------
CASE DESCRIPTION
 Site name/label:   Aquaforte
 Design case:       October 22
 FILE NAME:         C:\...top\Sara's Important Stuff\Cormix\Oct22\Oct22.prd
 Time stamp:        Sat Mar 26 12:06:03 2005

ENVIRONMENT PARAMETERS (metric units)
 Unbounded section
 HA    =      3.50  HD    =      2.64
 UA    =     0.250  F     =     0.032 USTAR =0.1589E-01
 UW    =     5.556 UWSTAR=0.6623E-02
 Uniform density environment
 STRCND=  U         RHOAM = 1020.0630

DISCHARGE PARAMETERS (metric units)
 BANK  =  LEFT      DISTB =     25.00
 D0    =     0.051 A0    =     0.002 H0    =      0.88
 THETA =      0.00  SIGMA =      0.00
 U0    =     7.398 Q0    =     0.015       =0.1500E-01
 RHO0  =  999.7422  DRHO0 =0.2032E+02  GP0   =0.1954E+00
 C0    = 0.4980E-03 CUNITS=  ppb
 IPOLL =  1         KS    =0.0000E+00  KD    =0.0000E+00

FLUX VARIABLES (metric units)
 Q0    =0.1500E-01  M0    =0.1110E+00  J0    =0.2930E-02  SIGNJ0=      1.0
 Associated length scales (meters)
 LQ    =     0.05  LM    =     3.55  Lm    =     1.33  Lb    =      0.19
                                     Lmp   =  99999.00  Lbp   =  99999.00

NON-DIMENSIONAL PARAMETERS
 FR0   =     74.25  R     =     29.59

FLOW CLASSIFICATION
 1111111111111111111111111111111111111111
 1  Flow class (CORMIX1)      =    H4-0   1
 1  Applicable layer depth HS =     2.64  1
 1111111111111111111111111111111111111111

MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS
 C0    = 0.5000E-03 CUNITS=  ppb
 NTOX  =  0
 NSTD  =  0
 REGMZ =  0
 XINT  =    175.00  XMAX  =    175.00

X-Y-Z COORDINATE SYSTEM:
    ORIGIN is located at the bottom and below the center of the port:
        25.00 m  from the LEFT  bank/shore.
    X-axis points downstream, Y-axis points to left, Z-axis points upward.
NSTEP = 15 display intervals per module
```

```
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN MOD101: DISCHARGE MODULE

       X         Y         Z         S         C         B
    0.00      0.00      0.88       1.0 0.498E+03    0.03

END OF MOD101: DISCHARGE MODULE
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

 Jet/plume transition motion in weak crossflow.

 Zone of flow establishment:              THETAE=      0.00  SIGMAE=      0.00
  LE    =      0.25  XE    =      0.25  YE    =      0.00  ZE    =      0.88

 Profile definitions:
   B = Gaussian 1/e (37%) half-width, normal to trajectory
   S = hydrodynamic centerline dilution
   C = centerline concentration (includes reaction effects, if any)

       X         Y         Z         S         C         B
    0.00      0.00      0.88       1.0 0.500E+03    0.03
    0.25      0.00      0.88       1.0 0.498E+03    0.03
    0.97      0.00      0.88       3.6 0.139E+03    0.10
    1.68      0.00      0.89       6.3 0.786E+02    0.16
    2.39      0.00      0.91       9.2 0.539E+02    0.22
    3.13      0.00      0.95      12.4 0.401E+02    0.27
    3.84      0.00      0.99      15.7 0.317E+02    0.33
    4.55      0.00      1.05      19.2 0.260E+02    0.38
    5.29      0.00      1.11      23.0 0.216E+02    0.43
    6.00      0.00      1.19      27.0 0.184E+02    0.48
    6.71      0.00      1.26      31.2 0.159E+02    0.52
    7.44      0.00      1.35      35.9 0.139E+02    0.57
    8.15      0.00      1.44      40.6 0.123E+02    0.62
    8.85      0.00      1.53      45.5 0.109E+02    0.67
    9.59      0.00      1.63      50.8 0.980E+01    0.71
   10.29      0.00      1.73      56.2 0.887E+01    0.76
   11.00      0.00      1.83      61.6 0.808E+01    0.80
 Cumulative travel time =          16. sec

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

  Control volume inflow:
       X         Y         Z         S         C         B
   11.00      0.00      1.83      61.6 0.808E+01    0.80

 Profile definitions:
   BV = Gaussian 1/e (37%) vertical thickness
   BH = Gaussian 1/e (37%) horizontal half-width, normal to trajectory
   ZU = upper plume boundary (Z-coordinate)
   ZL = lower plume boundary (Z-coordinate)
   S = hydrodynamic centerline dilution
```

C = centerline concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
10.20	0.00	2.64	61.6	0.808E-01	0.00	0.00	2.64	2.64
10.44	0.00	2.64	61.6	0.808E-01	0.63	0.31	2.64	2.01
10.68	0.00	2.64	61.6	0.808E-01	0.74	0.45	2.64	1.90
10.92	0.00	2.64	61.6	0.808E+01	0.82	0.55	2.64	1.82
11.16	0.00	2.64	61.7	0.807E+01	0.87	0.63	2.64	1.77
11.40	0.00	2.64	61.8	0.805E+01	0.91	0.70	2.64	1.73
11.64	0.00	2.64	62.1	0.802E+01	0.94	0.77	2.64	1.70
11.88	0.00	2.64	62.3	0.800E+01	0.97	0.83	2.64	1.67
12.12	0.00	2.64	62.4	0.798E+01	0.98	0.89	2.64	1.66
12.36	0.00	2.64	62.5	0.797E+01	0.99	0.94	2.64	1.65
12.60	0.00	2.64	62.5	0.796E+01	1.00	1.00	2.64	1.64

Cumulative travel time = 20. sec

END OF MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

BEGIN MOD155: WEAKLY DEFLECTED SURFACE/BOTTOM PLUME

SURFACE/BOTTOM PLUME into a co-flow (or counter-flow)

This flow region is INSIGNIFICANT in spatial extent and will be by-passed.

END OF MOD155: WEAKLY DEFLECTED SURFACE/BOTTOM PLUME

BEGIN MOD156: STRONGLY DEFLECTED SURFACE/BOTTOM PLUME

SPECIAL CO-FLOWING, COUNTER-FLOWING OR VERTICAL DISCHARGE CASE:
THIS FLOW REGION DOES NOT OCCUR.

END OF MOD156: STRONGLY DEFLECTED SURFACE/BOTTOM PLUME

** End of NEAR-FIELD REGION (NFR) **

The initial plume WIDTH values in the next far-field module will be
CORRECTED by a factor 1.38 to conserve the mass flux in the far-field!

BEGIN MOD141: BUOYANT AMBIENT SPREADING

Profile definitions:
BV = top-hat thickness, measured vertically
BH = top-hat half-width, measured horizontally in Y-direction
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic average (bulk) dilution
C = average (bulk) concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
12.60	0.00	2.64	62.5	0.796E+01	1.37	1.37	2.64	1.27
23.43	0.00	2.64	77.2	0.645E+01	0.78	2.97	2.64	1.86
34.26	0.00	2.64	87.6	0.569E+01	0.62	4.21	2.64	2.02
45.08	0.00	2.64	98.4	0.506E+01	0.56	5.28	2.64	2.08
55.91	0.00	2.64	110.9	0.449E+01	0.53	6.25	2.64	2.11

66.74	0.00	2.64	125.9	0.396E-01	0.53	7.16	2.64	2.11
77.56	0.00	2.64	143.7	0.346E-01	0.54	8.00	2.64	2.10
88.39	0.00	2.64	164.7	0.302E-01	0.56	8.81	2.64	2.08
99.22	0.00	2.64	189.0	0.263E-01	0.59	9.58	2.64	2.05
110.04	0.00	2.64	217.0	0.230E-01	0.63	10.32	2.64	2.01
120.87	0.00	2.64	248.7	0.200E-01	0.68	11.03	2.64	1.96
131.69	0.00	2.64	284.3	0.175E-01	0.73	11.72	2.64	1.91
142.52	0.00	2.64	324.0	0.154E-01	0.78	12.39	2.64	1.86
153.35	0.00	2.64	368.0	0.135E-01	0.85	13.05	2.64	1.79
164.17	0.00	2.64	416.2	0.120E-01	0.91	13.68	2.64	1.73
175.00	0.00	2.64	469.0	0.106E-01	0.98	14.31	2.64	1.66

Cumulative travel time = 669. sec

Simulation limit based on maximum specified distance = 175.00 m.
This is the REGION OF INTEREST limitation.

END OF MOD141: BUOYANT AMBIENT SPREADING

CORMIX1: Submerged Single Port Discharges End of Prediction File

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```
CORMIX1 PREDICTION FILE:
1111111111111111111111111111111111111111111111111111111111111111111111111111111111
                    CORNELL MIXING ZONE EXPERT SYSTEM
            Subsystem CORMIX1:  Submerged Single Port Discharges
 CORMIX-GI Version 4.1GT
-------------------------------------------------------------------------------
-------------------------------------------------------------------------------
CASE DESCRIPTION
 Site name/label:   Aquaforte
 Design case:       October 22
 FILE NAME:         C:\...top\Sara's Important Stuff\Cormix Oct22\Oct22.prd
 Time stamp:        Sat Mar 26 11:43:35 2005

ENVIRONMENT PARAMETERS (metric units)
 Unbounded section
 HA    =      3.50  HD    =      2.64
 UA    =     0.500  F     =     0.032 USTAR =0.3177E-01
 UW    =     5.556 UWSTAR=0.6623E-02
 Uniform density environment
 STRCND=  U         RHOAM = 1020.0630

DISCHARGE PARAMETERS (metric units)
 BANK  =  LEFT      DISTB =     25.00
 D0    =     0.051 A0    =     0.002 H0    =      0.88
 THETA =      0.00  SIGMA =      0.00
 U0    =     7.398 Q0    =     0.015       =0.1500E-01
 RHO0  =  999.7422  DRHO0 =0.2032E+02  GP0   =0.1954E+00
 C0    = 0.4980E+03 CUNITS=  ppb
 IPOLL =  1         KS    =0.0000E-00  KD    =0.0000E+00

FLUX VARIABLES (metric units)
 Q0    =0.1500E-01  M0    =0.1110E+00  J0    =0.2930E-02  SIGNJ0=      1.0
 Associated length scales (meters)
 LQ    =     0.05  LM    =     3.55  Lm    =     0.67  Lb    =     0.02
                                     Lmp   =  99999.00  Lbp   =  99999.00

NON-DIMENSIONAL PARAMETERS
 FR0   =    74.25  R     =    14.80

FLOW CLASSIFICATION
 111111111111111111111111111111111111111111
 1  Flow class (CORMIX1)      =    H2     1
 1  Applicable layer depth HS =     2.64  1
 111111111111111111111111111111111111111111

MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS
 C0    = 0.5000E-03 CUNITS=  ppb
 NTOX  =  0
 NSTD  =  0
 REGMZ =  0
 XINT  =    175.00  XMAX  =    175.00

X-Y-Z COORDINATE SYSTEM:
    ORIGIN is located at the bottom and below the center of the port:
        25.00 m  from the LEFT  bank/shore.
    X-axis points downstream, Y-axis points to left, Z-axis points upward.
NSTEP = 15 display intervals per module
```

```
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN MOD101: DISCHARGE MODULE

       X        Y        Z        S        C        B
    0.00     0.00     0.88      1.0 0.500E+03    0.03

END OF MOD101: DISCHARGE MODULE
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

 Jet-like motion in weak crossflow.

 Zone of flow establishment:              THETAE=      0.00  SIGMAE=      0.00
  LE    =      0.25  XE    =      0.25  YE    =      0.00  ZE    =      0.88

 Profile definitions:
   B = Gaussian 1/e (37%) half-width, normal to trajectory
   S = hydrodynamic centerline dilution
   C = centerline concentration (includes reaction effects, if any)

       X        Y        Z        S        C        B
    0.00     0.00     0.88      1.0 0.500E+03    0.03
    0.25     0.00     0.88      1.0 0.498E+03    0.03
    1.52     0.00     0.89      5.7 0.869E+02    0.13
    2.79     0.00     0.91     10.9 0.459E+02    0.21
    4.08     0.00     0.96     16.4 0.304E+02    0.27
    5.35     0.00     1.01     22.1 0.225E+02    0.33
    6.64     0.00     1.08     28.2 0.176E+02    0.38
    7.90     0.00     1.14     34.5 0.144E+02    0.43
    9.20     0.00     1.22     41.1 0.121E+02    0.48
   10.46     0.00     1.29     47.8 0.104E+02    0.52
   11.73     0.00     1.37     54.7 0.910E+01    0.56
   13.02     0.00     1.45     61.9 0.805E+01    0.60
   14.28     0.00     1.53     69.1 0.721E+01    0.64
   15.57     0.00     1.61     76.6 0.650E+01    0.68
   16.84     0.00     1.69     84.0 0.593E+01    0.71
   18.13     0.00     1.78     91.8 0.543E+01    0.75
   19.39     0.00     1.86     99.4 0.501E+01    0.78
 Cumulative travel time =          24. sec

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION
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BEGIN MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

  Control volume inflow:
       X        Y        Z        S        C        B
   19.39     0.00     1.86     99.4 0.501E+01    0.78

 Profile definitions:
   BV = top-hat thickness, measured vertically
   BH = top-hat half-width, measured horizontally in Y-direction
   ZU = upper plume boundary (Z-coordinate)
   ZL = lower plume boundary (Z-coordinate)
   S  = hydrodynamic average (bulk) dilution
```

C = average (bulk) concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
18.61	0.00	2.64	99.4	0.501E+01	0.00	0.00	2.64	2.64
18.85	0.00	2.64	99.4	0.501E+01	1.00	0.50	2.64	1.64
19.08	0.00	2.64	99.4	0.501E+01	1.19	0.71	2.64	1.45
19.31	0.00	2.64	99.4	0.501E+01	1.31	0.87	2.64	1.33
19.55	0.00	2.64	102.2	0.487E+01	1.39	1.01	2.64	1.25
19.78	0.00	2.64	114.8	0.434E+01	1.46	1.13	2.64	1.18
20.02	0.00	2.64	132.3	0.376E+01	1.51	1.23	2.64	1.13
20.25	0.00	2.64	148.3	0.336E+01	1.55	1.33	2.64	1.09
20.49	0.00	2.64	159.2	0.313E+01	1.57	1.42	2.64	1.07
20.72	0.00	2.64	165.2	0.302E+01	1.59	1.51	2.64	1.05
20.96	0.00	2.64	169.0	0.295E+01	1.59	1.59	2.64	1.05

Cumulative travel time = 27. sec

END OF MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

** End of NEAR-FIELD REGION (NFR) **

BEGIN MOD141: BUOYANT AMBIENT SPREADING

Profile definitions:
BV = top-hat thickness, measured vertically
BH = top-hat half-width, measured horizontally in Y-direction
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic average (bulk) dilution
C = average (bulk) concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
20.96	0.00	2.64	169.0	0.295E+01	1.59	1.59	2.64	1.05
22.59	0.00	2.64	173.1	0.288E+01	1.54	1.69	2.64	1.10
24.23	0.00	2.64	177.1	0.281E+01	1.49	1.79	2.64	1.15
25.86	0.00	2.64	181.3	0.275E+01	1.45	1.88	2.64	1.19
27.50	0.00	2.64	185.5	0.269E+01	1.41	1.97	2.64	1.23
29.13	0.00	2.64	189.8	0.262E+01	1.38	2.06	2.64	1.26
30.77	0.00	2.64	194.2	0.256E+01	1.36	2.14	2.64	1.28
32.41	0.00	2.64	198.7	0.251E+01	1.34	2.23	2.64	1.30
34.04	0.00	2.64	203.4	0.245E+01	1.32	2.31	2.64	1.32
35.68	0.00	2.64	208.3	0.239E+01	1.31	2.39	2.64	1.33
37.31	0.00	2.64	213.3	0.233E+01	1.29	2.47	2.64	1.35
38.95	0.00	2.64	218.5	0.228E+01	1.28	2.55	2.64	1.36
40.59	0.00	2.64	223.9	0.222E+01	1.28	2.63	2.64	1.36
42.22	0.00	2.64	229.5	0.217E+01	1.27	2.71	2.64	1.37
43.86	0.00	2.64	235.3	0.212E+01	1.27	2.78	2.64	1.37
45.49	0.00	2.64	241.2	0.206E+01	1.27	2.86	2.64	1.37

Cumulative travel time = 76. sec

END OF MOD141: BUOYANT AMBIENT SPREADING

Bottom coordinate for FAR-FIELD is determined by average depth, ZFB = -0.86m

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BEGIN MOD161: PASSIVE AMBIENT MIXING IN UNIFORM AMBIENT

Vertical diffusivity (initial value) = 0.168E-01 m^2/s

Horizontal diffusivity (initial value) = 0.608E-02 m^2/s

Profile definitions:
BV = Gaussian s.d.*sqrt(pi/2) (46%) thickness, measured vertically
= or equal to layer depth, if fully mixed
BH = Gaussian s.d.*sqrt(pi/2) (46%) half-width,
measured horizontally in Y-direction
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic centerline dilution
C = centerline concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
45.49	0.00	2.64	241.2	0.206E+01	1.27	2.86	2.64	1.37
54.13	0.00	2.64	252.3	0.197E+01	1.30	2.91	2.64	1.34
62.76	0.00	2.64	264.0	0.189E+01	1.33	2.97	2.64	1.31
71.39	0.00	2.64	276.3	0.180E+01	1.37	3.03	2.64	1.27
80.03	0.00	2.64	289.3	0.172E+01	1.40	3.09	2.64	1.24
88.66	0.00	2.64	302.9	0.164E+01	1.44	3.15	2.64	1.20
97.30	0.00	2.64	317.3	0.157E+01	1.48	3.21	2.64	1.16
105.93	0.00	2.64	332.4	0.150E+01	1.53	3.27	2.64	1.11
114.56	0.00	2.64	348.2	0.143E+01	1.57	3.33	2.64	1.07
123.20	0.00	2.64	364.9	0.136E+01	1.61	3.39	2.64	1.03
131.83	0.00	2.64	382.4	0.130E+01	1.66	3.45	2.64	0.98
140.46	0.00	2.64	400.8	0.124E+01	1.71	3.51	2.64	0.93
149.10	0.00	2.64	420.1	0.119E+01	1.76	3.58	2.64	0.88
157.73	0.00	2.64	440.3	0.113E+01	1.82	3.64	2.64	0.82
166.37	0.00	2.64	461.5	0.108E+01	1.87	3.70	2.64	0.77
175.00	0.00	2.64	483.6	0.103E+01	1.93	3.76	2.64	0.71

Cumulative travel time = 335. sec

Simulation limit based on maximum specified distance = 175.00 m.
This is the REGION OF INTEREST limitation.

END OF MOD161: PASSIVE AMBIENT MIXING IN UNIFORM AMBIENT

CORMIX1: Submerged Single Port Discharges End of Prediction File
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CORMIX1 PREDICTION FILE:
1111111111111111111111111111111111111111111111111111111111111111111111111111
                    CORNELL MIXING ZONE EXPERT SYSTEM
             Subsystem CORMIX1:  Submerged Single Port Discharges
 CORMIX-GI Version 4.1GT
------------------------------------------------------------------------------
------------------------------------------------------------------------------
CASE DESCRIPTION
 Site name/label:
 Design case:
 FILE NAME:          C:\...top\Sara's Important Stuff\Cormix\Oct22\Oct22.prd
 Time stamp:         Tue Mar 29 21:25:52 2005

ENVIRONMENT PARAMETERS (metric units)
 Unbounded section
 HA    =       3.50  HD    =       2.64
 UA    =      0.700  F     =      0.032 USTAR =0.4448E-01
 UW    =      5.000 UWSTAR=0.5890E-02
 Uniform density environment
 STRCND=  U          RHOAM = 1020.0600

DISCHARGE PARAMETERS (metric units)
 BANK  =  LEFT       DISTB =     25.00
 D0    =      0.051 A0    =      0.002 H0    =      0.88
 THETA =       0.00 SIGMA =       0.00
 U0    =      0.740 Q0    =      0.002       =0.1500E-02
 RHO0  =   999.7833 DRHO0 =0.2028E+02  GP0   =0.1949E+00
 C0    = 0.4980E+03 CUNITS=  ppb
 IPOLL =  1          KS    =0.0000E+00  KD    =0.0000E+00

FLUX VARIABLES (metric units)
 Q0    =0.1500E-02  M0    =0.1110E-02  J0    =0.2924E-03  SIGNJ0=      1.0
 Associated length scales (meters)
 LQ    =      0.05  LM    =      0.36  Lm    =      0.05  Lb    =      0.00
                                       Lmp   =  99999.00  Lbp   =  99999.00

NON-DIMENSIONAL PARAMETERS
 FR0   =      7.43  R     =      1.06

FLOW CLASSIFICATION
 11111111111111111111111111111111111111
 1  Flow class (CORMIX1)      =    H1     1
 1  Applicable layer depth HS =     2.64  1
 11111111111111111111111111111111111111

MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS
 C0    = 0.5000E+03 CUNITS=  ppb
 NTOX  =  0
 NSTD  =  0
 REGMZ =  0
 XINT  =    175.00  XMAX  =    175.00

X-Y-Z COORDINATE SYSTEM:
    ORIGIN is located at the bottom and below the center of the port:
        25.00 m  from the LEFT  bank/shore.
    X-axis points downstream, Y-axis points to left, Z-axis points upward.
NSTEP = 15 display intervals per module
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BEGIN MOD101: DISCHARGE MODULE

       X         Y         Z         S         C         B
    0.00      0.00      0.88       1.0 0.500E+03    0.03

END OF MOD101: DISCHARGE MODULE
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

 Jet/plume transition motion in strong crossflow.

 Zone of flow establishment:              THETAE=      0.00  SIGMAE=      0.00
  LE    =      0.24  XE    =      0.24  YE    =      0.00  ZE    =      0.88

 Profile definitions:
   B = Gaussian 1/e (37%) half-width, normal to trajectory
   S = hydrodynamic centerline dilution
   C = centerline concentration (includes reaction effects, if any)

       X         Y         Z         S         C         B
    0.00      0.00      0.88       1.0 0.500E+03    0.03
    0.24      0.00      0.88       1.1 0.466E+03    0.03
    2.73      0.00      1.12       5.3 0.946E+02    0.05
    5.22      0.00      1.26      14.2 0.352E+02    0.08
    7.71      0.00      1.38      25.4 0.196E+02    0.11
   10.21      0.00      1.49      38.3 0.130E+02    0.13
   12.70      0.00      1.58      52.5 0.949E+01    0.16
   15.19      0.00      1.67      67.8 0.735E+01    0.18
   17.69      0.00      1.75      84.1 0.592E+01    0.20
   20.19      0.00      1.83     101.3 0.492E+01    0.22
   22.68      0.00      1.90     119.2 0.418E+01    0.24
   25.18      0.00      1.98     138.0 0.361E+01    0.26
   27.67      0.00      2.04     157.3 0.317E+01    0.27
   30.17      0.00      2.11     177.3 0.281E+01    0.29
   32.67      0.00      2.18     197.9 0.252E+01    0.31
   35.16      0.00      2.24     219.1 0.227E+01    0.32
   37.66      0.00      2.30     240.8 0.207E+01    0.34
 Cumulative travel time =          56. sec

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
BEGIN MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

  Control volume inflow:
       X         Y         Z         S         C         B
    37.66      0.00      2.30     240.8 0.207E+01    0.34

 Profile definitions:
   BV = top-hat thickness, measured vertically
   BH = top-hat half-width, measured horizontally in Y-direction
   ZU = upper plume boundary (Z-coordinate)
   ZL = lower plume boundary (Z-coordinate)
   S  = hydrodynamic average (bulk) dilution
```

C = average (bulk) concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
37.32	0.00	2.64	240.8	0.207E+01	0.00	0.00	2.64	2.64
37.42	0.00	2.64	240.8	0.207E+01	0.42	0.21	2.64	2.22
37.52	0.00	2.64	240.8	0.207E+01	0.49	0.30	2.64	2.15
37.62	0.00	2.64	240.8	0.207E+01	0.54	0.36	2.64	2.10
37.72	0.00	2.64	247.4	0.201E+01	0.58	0.42	2.64	2.06
37.83	0.00	2.64	278.1	0.179E+01	0.61	0.47	2.64	2.03
37.93	0.00	2.64	320.5	0.155E+01	0.63	0.51	2.64	2.01
38.03	0.00	2.64	359.1	0.139E+01	0.64	0.55	2.64	2.00
38.13	0.00	2.64	385.6	0.129E+01	0.65	0.59	2.64	1.99
38.23	0.00	2.64	400.0	0.125E+01	0.66	0.63	2.64	1.98
38.33	0.00	2.64	409.3	0.122E+01	0.66	0.66	2.64	1.98

Cumulative travel time = 57. sec

END OF MOD131: LAYER BOUNDARY/TERMINAL LAYER APPROACH

** End of NEAR-FIELD REGION (NFR) **

BEGIN MOD141: BUOYANT AMBIENT SPREADING

Discharge is non-buoyant or weakly buoyant.
Therefore BUOYANT SPREADING REGIME is ABSENT.

END OF MOD141: BUOYANT AMBIENT SPREADING

Bottom coordinate for FAR-FIELD is determined by average depth, ZFB = -0.86m

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BEGIN MOD161: PASSIVE AMBIENT MIXING IN UNIFORM AMBIENT

Vertical diffusivity (initial value) = 0.235E-01 m^2/s
Horizontal diffusivity (initial value) = 0.866E-03 m^2/s

Profile definitions:
BV = Gaussian s.d.*sqrt(pi/2) (46%) thickness, measured vertically
= or equal to layer depth, if fully mixed
BH = Gaussian s.d.*sqrt(pi/2) (46%) half-width,
measured horizontally in Y-direction
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic centerline dilution
C = centerline concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
38.33	0.00	2.64	409.3	0.122E+01	0.66	0.66	2.64	1.98
47.44	0.00	2.64	511.2	0.974E+00	0.79	0.69	2.64	1.85
56.55	0.00	2.64	639.4	0.779E+00	0.96	0.72	2.64	1.68
65.67	0.00	2.64	791.8	0.629E+00	1.14	0.74	2.64	1.50
74.78	0.00	2.64	963.3	0.517E+00	1.34	0.77	2.64	1.30
83.89	0.00	2.64	1148.2	0.434E+00	1.54	0.80	2.64	1.10
93.00	0.00	2.64	1342.3	0.371E+00	1.74	0.83	2.64	0.90
102.11	0.00	2.64	1543.1	0.323E+00	1.93	0.86	2.64	0.71
111.22	0.00	2.64	1749.0	0.285E+00	2.11	0.89	2.64	0.53
120.33	0.00	2.64	1959.2	0.254E+00	2.29	0.92	2.64	0.35
129.44	0.00	2.64	2173.4	0.229E+00	2.46	0.95	2.64	0.18

138.56	0.00	2.64	2391.6	0.208E+00	2.62	0.98	2.64	0.02
147.67	0.00	2.64	2613.7	0.191E+00	2.78	1.01	2.64	-0.14
156.78	0.00	2.64	2839.8	0.175E+00	2.93	1.04	2.64	-0.29
165.89	0.00	2.64	3069.9	0.162E+00	3.07	1.07	2.64	-0.43
175.00	0.00	2.64	3304.3	0.151E+00	3.21	1.10	2.64	-0.57

Cumulative travel time = 252. sec

Simulation limit based on maximum specified distance = 175.00 m.
This is the REGION OF INTEREST limitation.

END OF MOD161: PASSIVE AMBIENT MIXING IN UNIFORM AMBIENT

CORMIX1: Submerged Single Port Discharges End of Prediction File

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